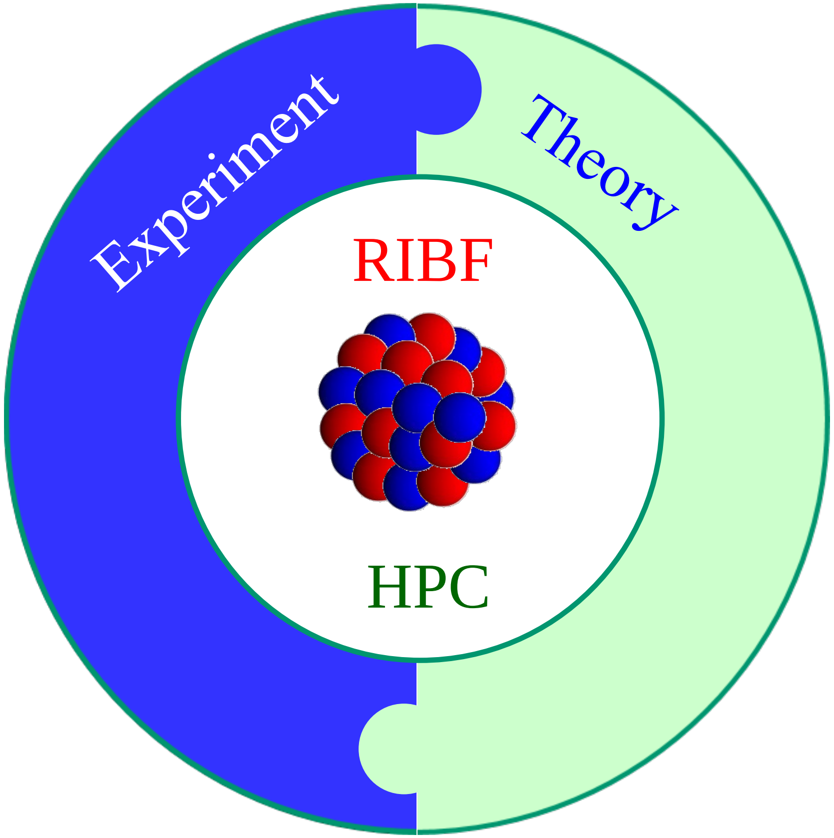
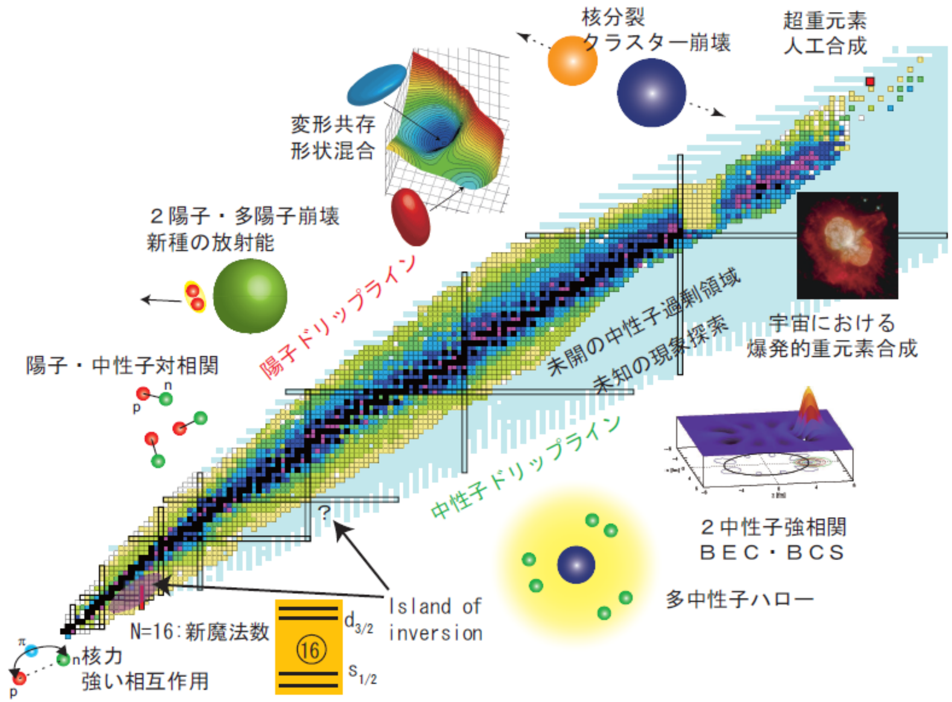
RIBF/post-RIBF and theory-experiment coupling

Kouichi Hagino
Tohoku University, Sendai, Japan



RIBF Theory Forum : white paper (2008)

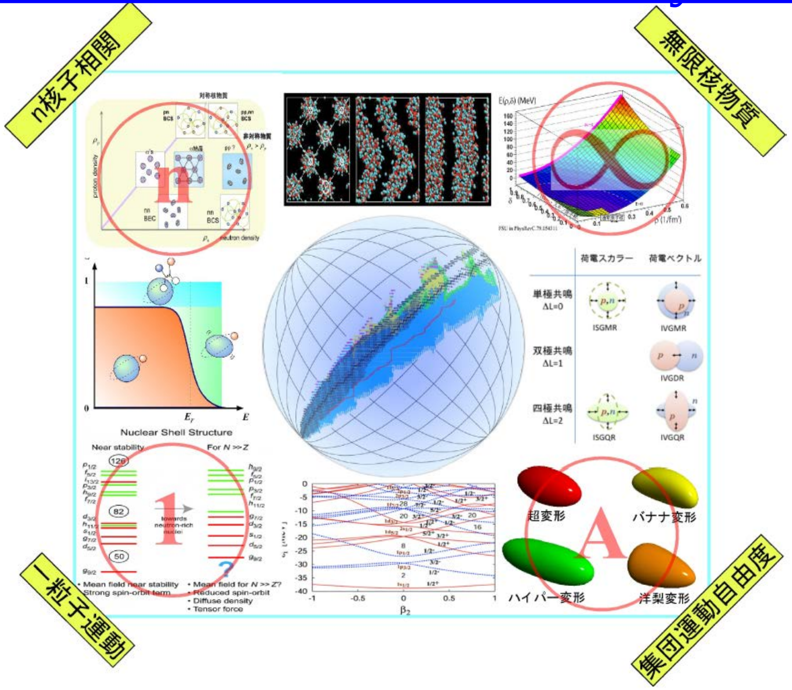


RIBF theory forum
the first members (2005 - 2014):

Itagaki, Utsuno, Kanada-En'yo, Ogata, Ono, Kohama, Sakurai, Nakatsukasa, Hagino, Honma, Matsuo, Mochizuki, Yabana

- ✓ Unveil new properties of atomic nuclei by controlling the proton and neutron numbers
- ✓ Explore the new phases and dynamics of nuclear matter at several proton and neutron densities
- ✓ Understand the origin of elements and several nuclear phenomena in the universe
- ✓ Challenge the physics of superheavy elements
- ✓ Systematize microscopic nuclear many-body theories

Report on future of nuclear physics in Japan
(working group on unstable nuclei: chaired by Aoi-san) 2013



"Six view points for research of unstable nuclei"

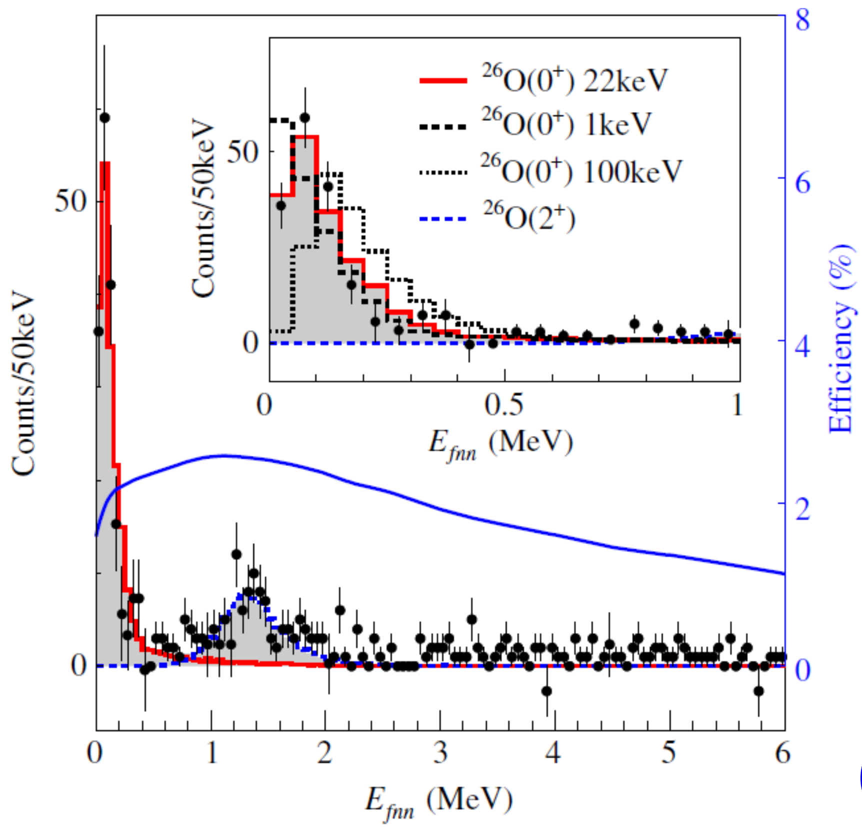
- ✓ the limit of existence: exploration of terra incognita
- ✓ single-particle motions and magic numbers
- ✓ n-nucleon correlations
- ✓ deformations
- ✓ EOS
- ✓ nuclear astrophysics

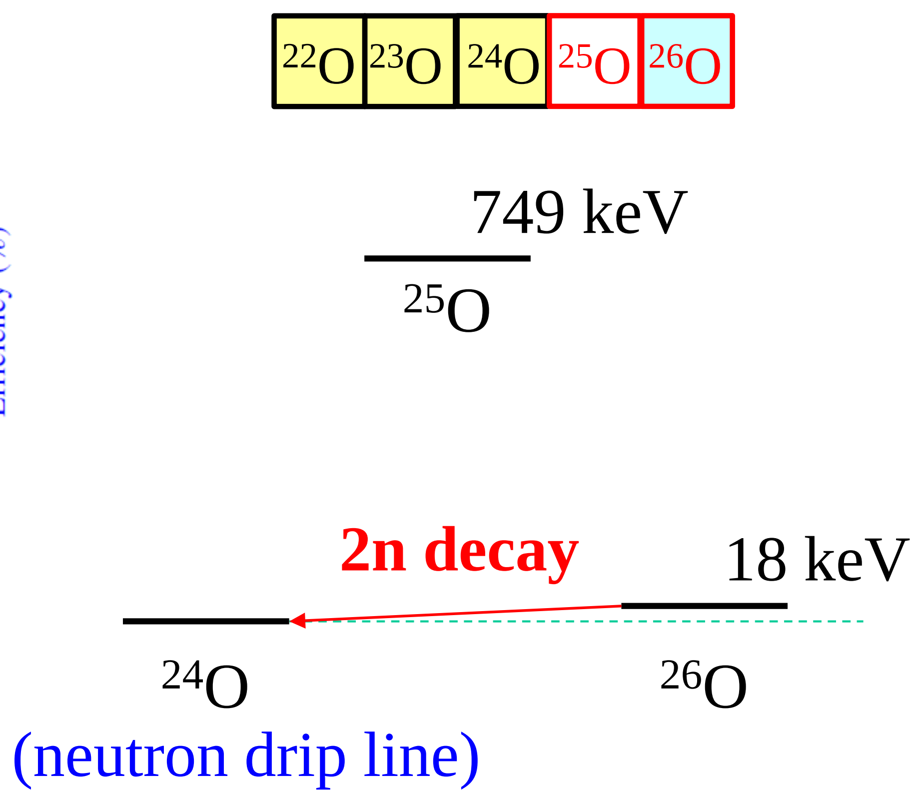
✓ the limit of existence: exploration of terra incognita

PRL **116,** 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

Y. Kondo,[1] T. Nakamura,[1] R. Tanaka,[1] R. Minakata,[1] S. Ogoshi,[1] N. A. Orr,[2] N. L. Achouri,[2] T. Aumann,[3,4] H. Baba,[5] F. Delaunay,[2] P. Doornenbal,[5] N. Fukuda,[5] J. Gibelin,[2] J. W. Hwang,[6] N. Inabe,[5] T. Isobe,[5] D. Kameda,[5] D. Kanno,[1] S. Kim,[6] N. Kobayashi,[1] T. Kobayashi,[7] T. Kubo,[5] S. Leblond,[2] J. Lee,[5] F. M. Marqués,[2] T. Motobayashi,[5] D. Murai,[8] T. Murakami,[9] K. Muto,[7] T. Nakashima,[1] N. Nakatsuka,[9] A. Navin,[10] S. Nishi,[1] H. Otsu,[5] H. Sato,[5] Y. Satou,[6] Y. Shimizu,[5] H. Suzuki,[5] K. Takahashi,[7] H. Takeda,[5] S. Takeuchi,[5] Y. Togano,[4,1] A. G. Tuff,[11] M. Vandebrouck,[12] and K. Yoneda[5]





✓ Two-neutron decays

PRL **116,** 102503 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Nucleus ^{26}O: A Barely Unbound System beyond the Drip Line

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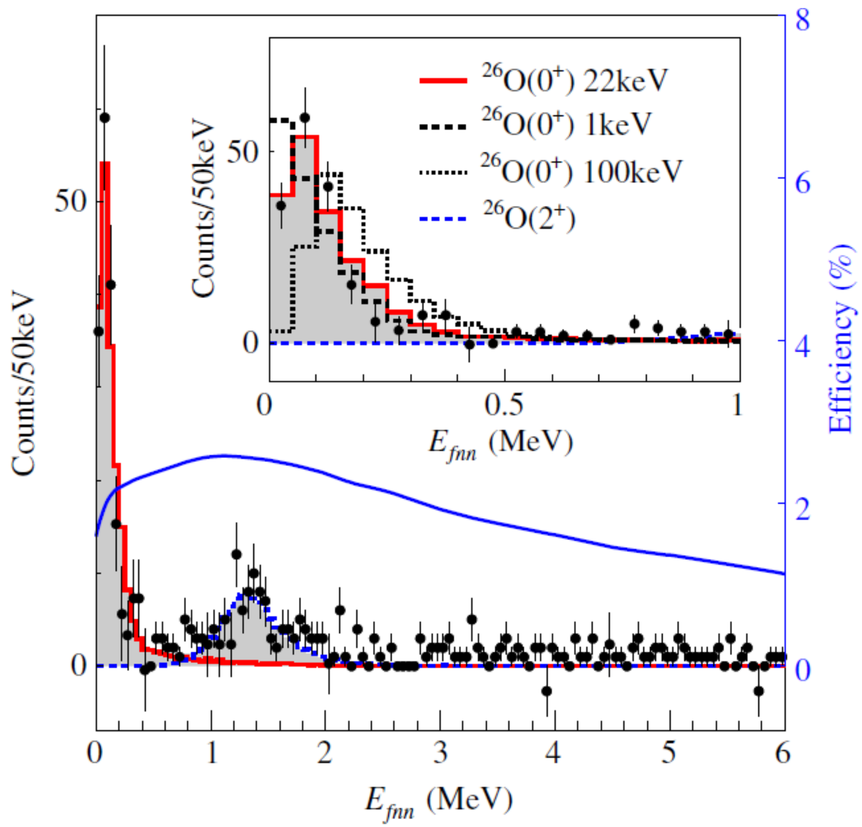
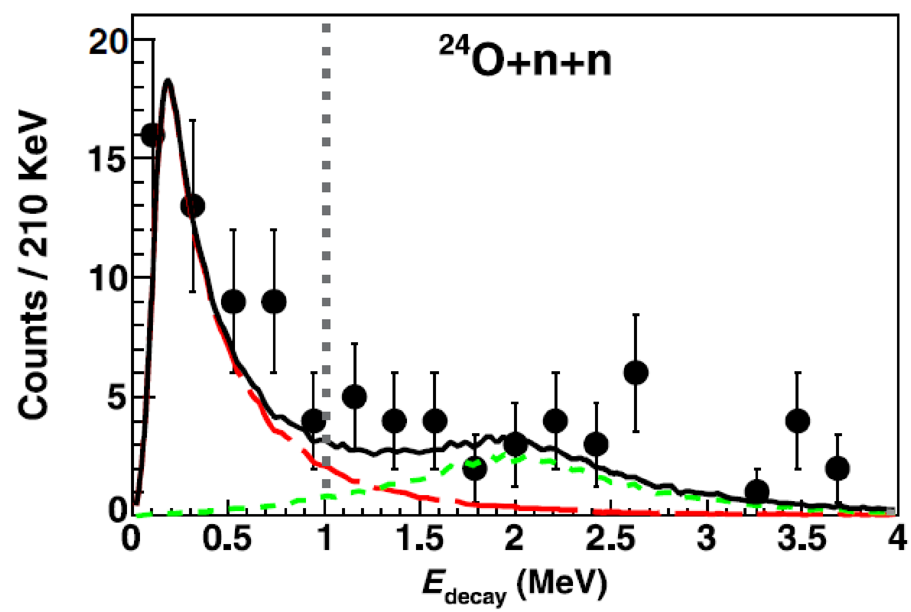
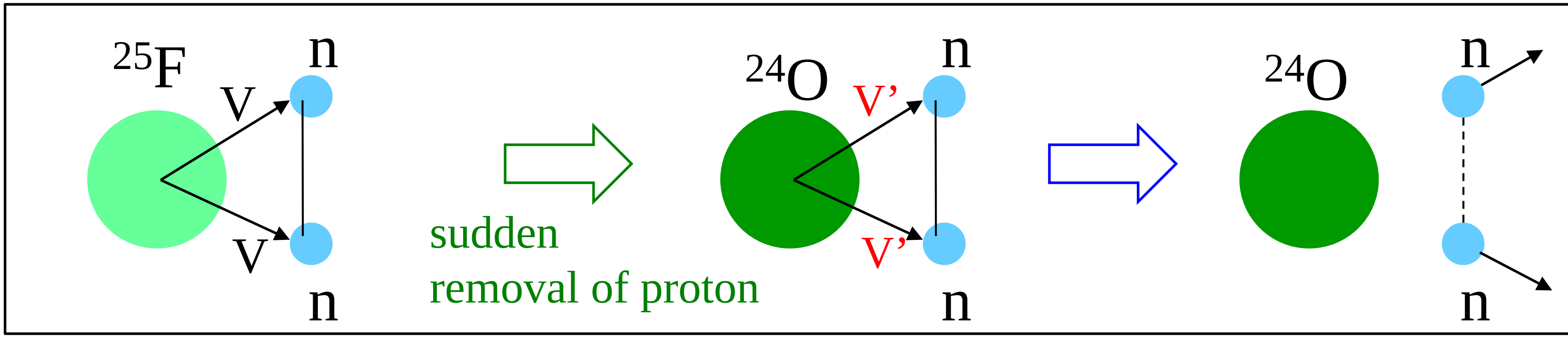


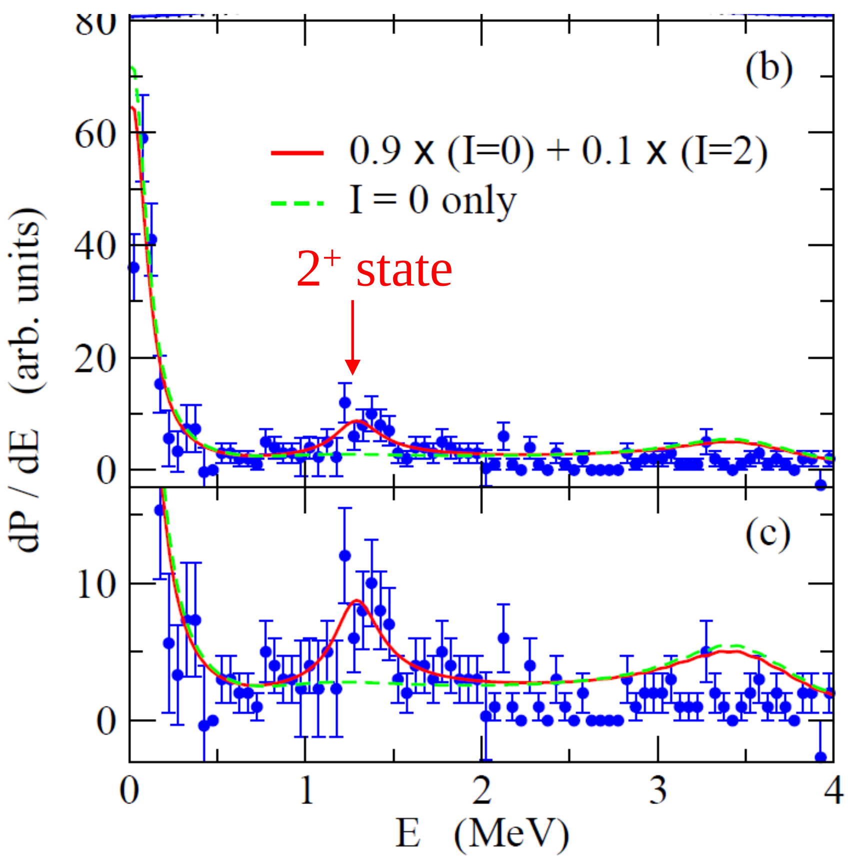
cf. previous MSU data



E. Lunderberg et al., PRL108 (‘12) 142503

✓ Two-neutron decays



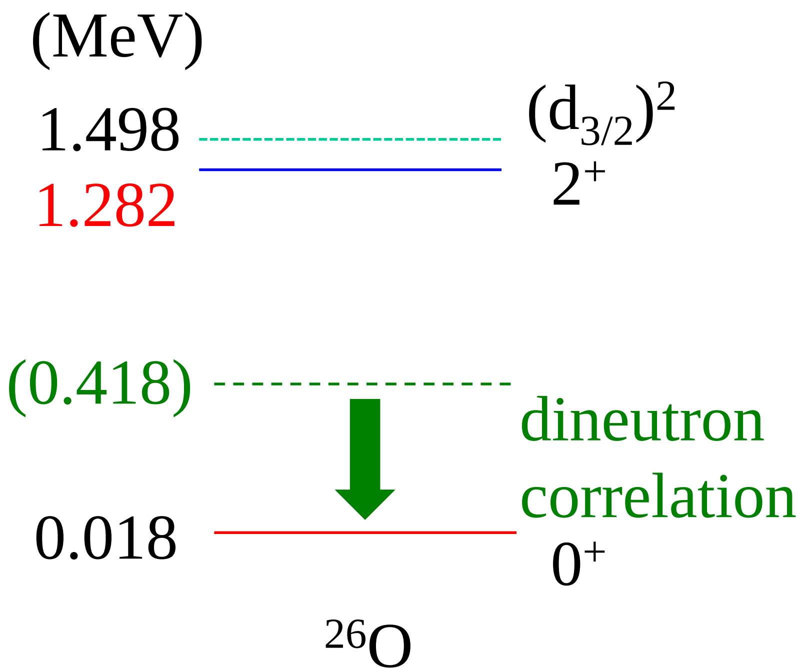


Three-body model calculation

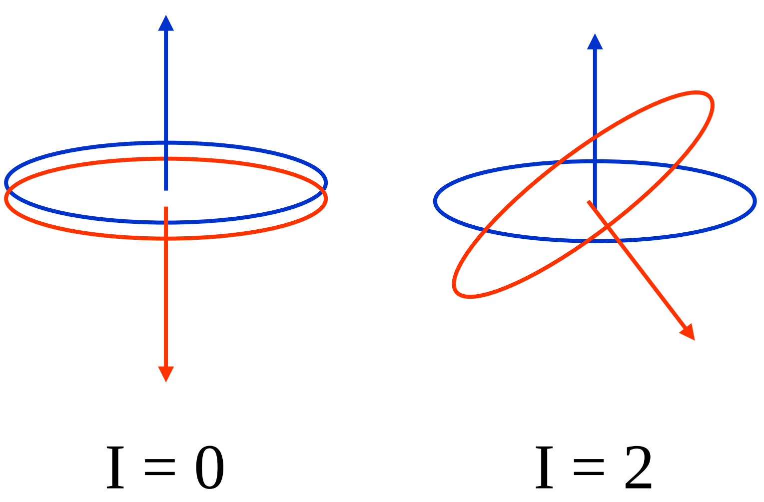
K.H. and H. Sagawa, PRC93 ('16)

✓ good reproduction of the data (both g.s. and the 2^+ state)

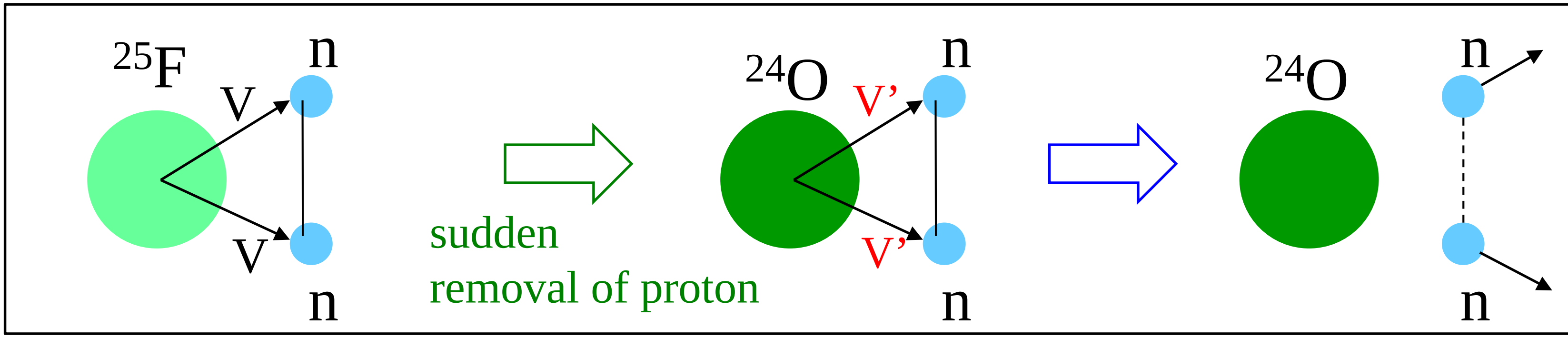
	^{25}O $(3/2^+)$	^{26}O (2^+)
Experiment	+ 749 (10) keV	$1.28^{+0.11}_{-0.08}$ MeV
USDA	1301 keV	2.4 MeV
chiral NN+3N	742 keV	1.64 MeV
continuum SM	1002 keV	1.87 MeV
3-body model (Hagino-Sagawa)	749 keV (input)	**1.282 MeV**

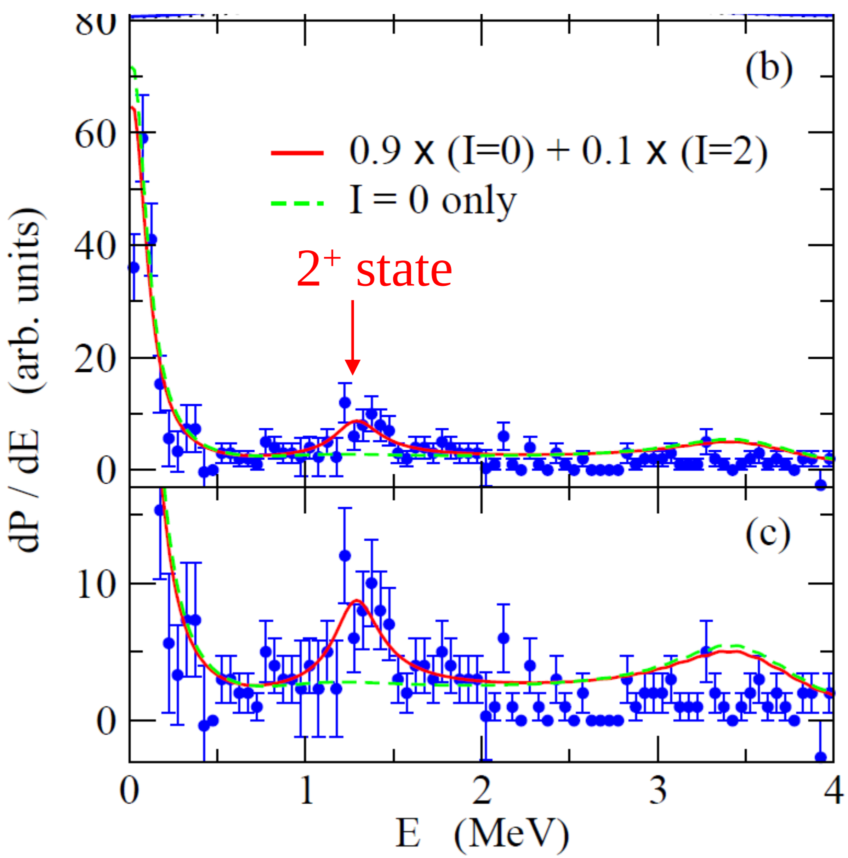


K.H. and H. Sagawa, PRC93 ('16)



✓ Two-neutron decays



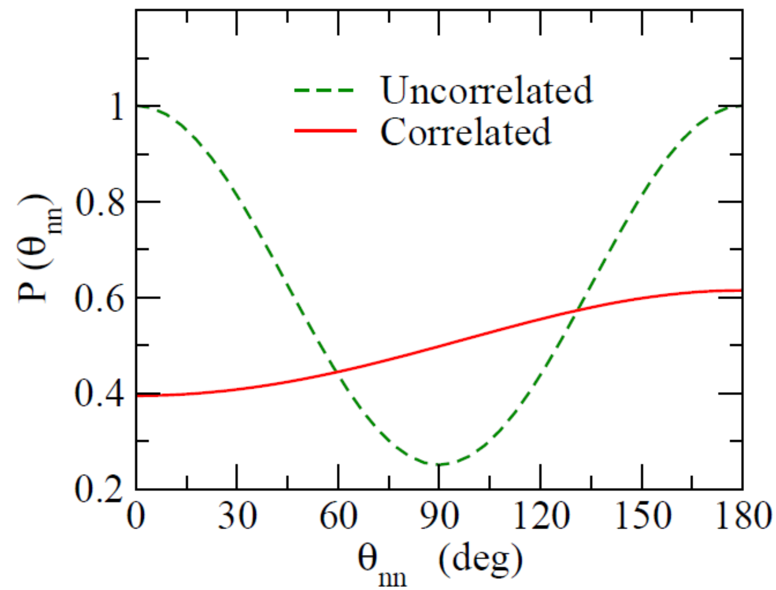


Three-body model calculation

K.H. and H. Sagawa, PRC93 ('16)

✓ good reproduction of the data

✓ prediction for angular distribut.

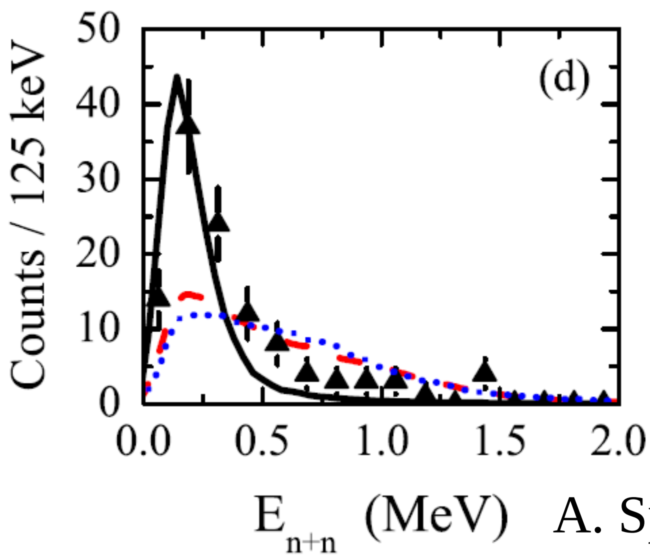


Future perspectives (two-neutron and multi-neutron decays):

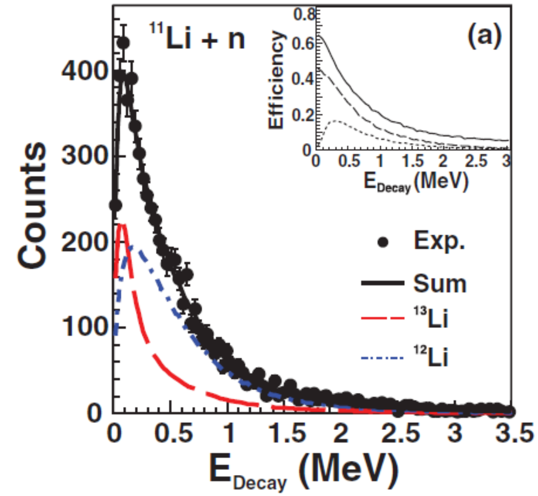
- MSU data

^{12}Be	^{13}Be	^{14}Be	^{15}Be	^{16}Be

^{9}Li	^{10}Li	^{11}Li	^{12}Li	^{13}Li



A. Spyrou et al., PRL108('12)

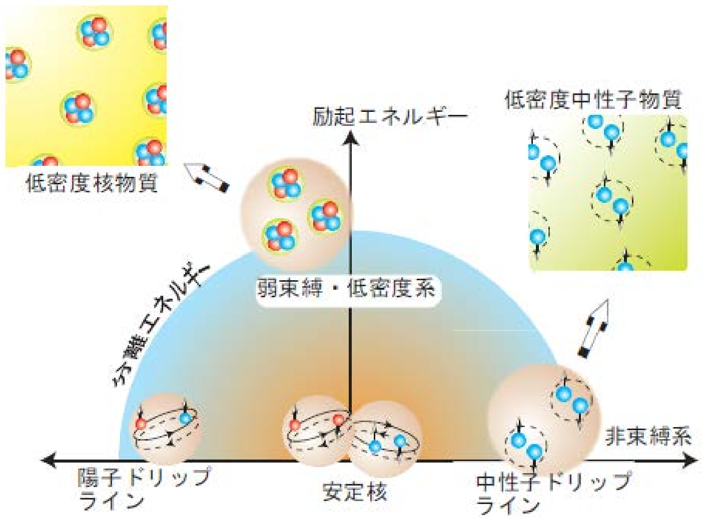


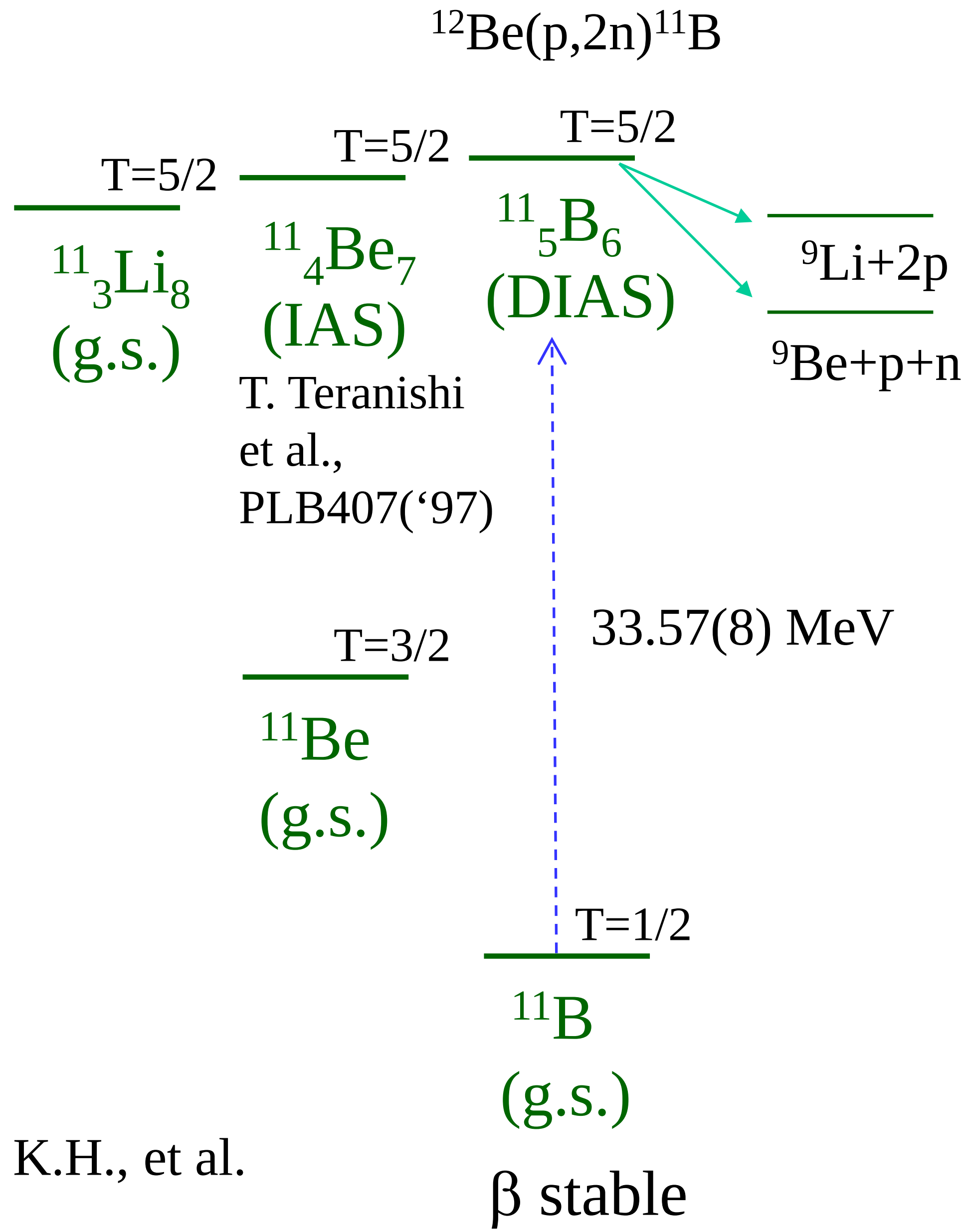
Z. Kohley et al., PRC87('13)

- ✓ better data with RIBF?
- ✓ measurement for the angular distribution?
- ✓ measurement of spin of emitted neutrons?
- ✓ role of three-body interaction?
- ✓ extension of the three-body model: deformed core / core+4n model

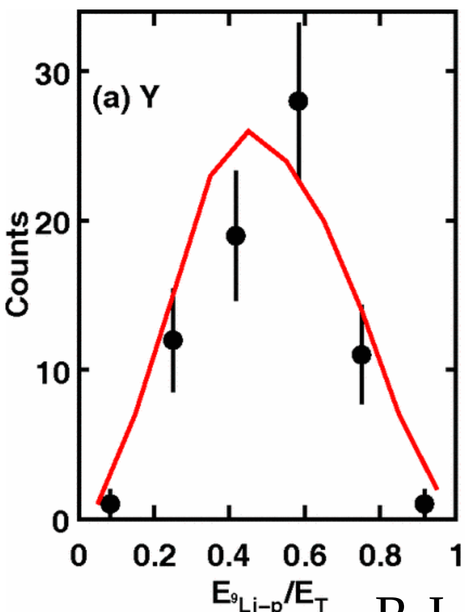
- ^{28}O experiment (Y. Kondo et al.)

Future perspectives (two-neutron and multi-neutron decays):





T. Teranishi et al., PLB407('97)



2p decay of double-IAS of ^{11}Li (^{11}B)

↕

g.s. of ^{11}Li

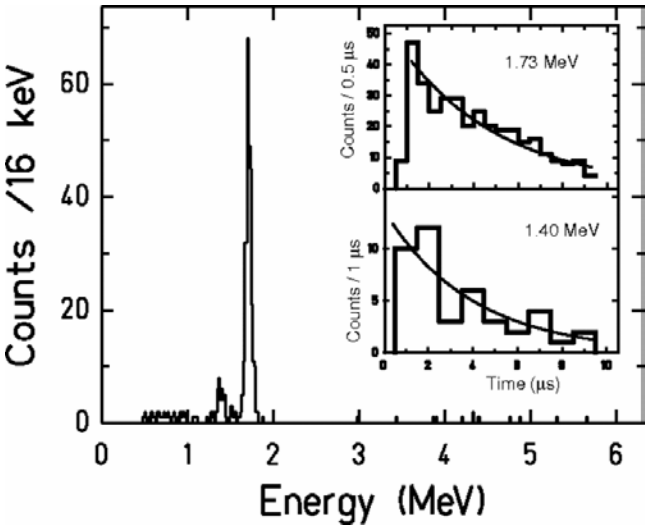
R.J. Charity, L. Sobotka, K.H., et al. PRC86('12)041307(R)

Future perspectives (two-neutron and multi-neutron decays):

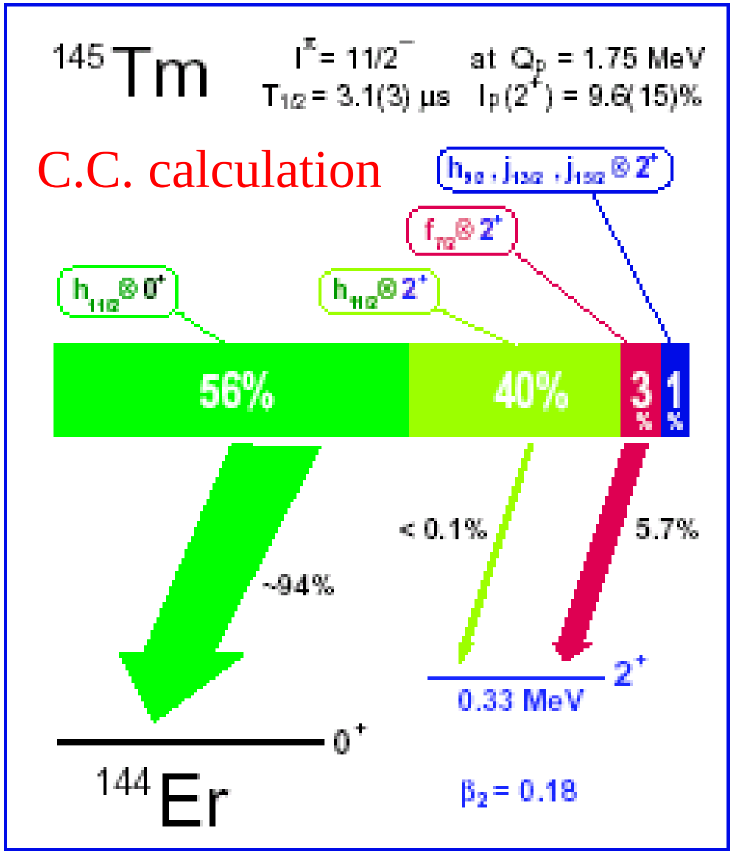
RIBF → post-RIBF: light/medium-heavy → med.-heavy/heavy nuclei

cf. one proton decay of medium-heavy proton-rich nuclei

Spherical emitter: $^{145}_{69}$Tm (Oak Ridge)



M. Karny, …., K.H., et al., PRL90('03)012502



cf. discovery of new p-emitters at RIBF:

^{93}Ag, ^{89}Rh, I. Celikovic et al., PRL116('16)

Calc.

$T_{1/2}$=3.0 ± 0.4 μs

I_p=5.7±0.3 %

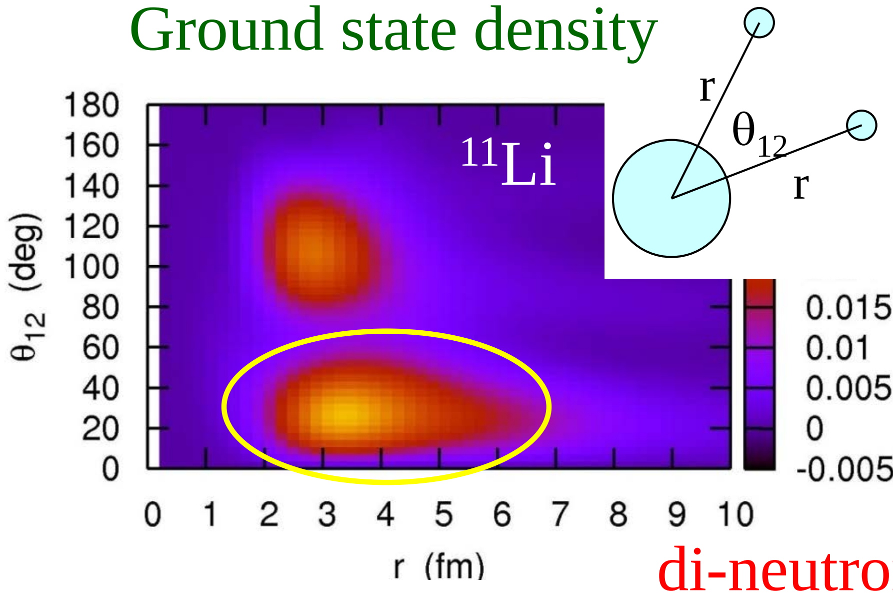
- one-neutron decay of medium-heavy neutron-rich nuclei (from an excited state)?
- two-neutron decay?

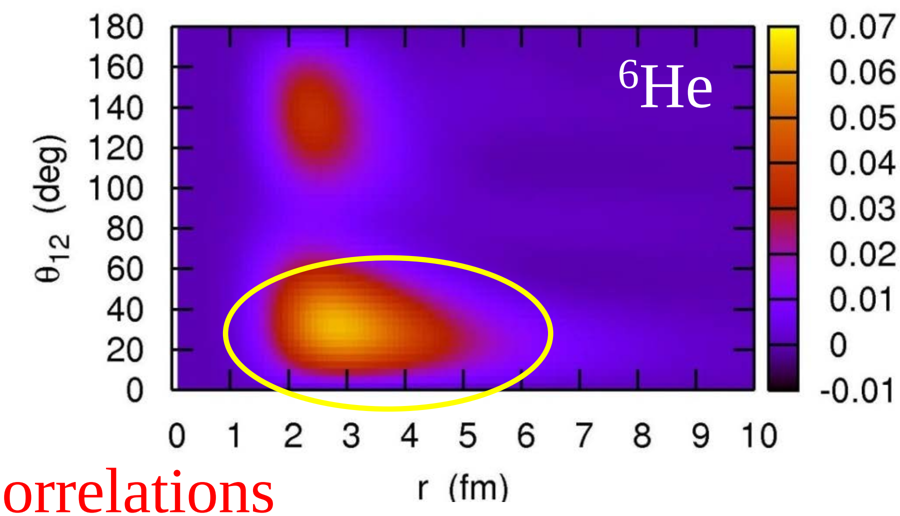
✓ nn correlations

three-body model calculations for **Borromean** nuclei

Ground state density

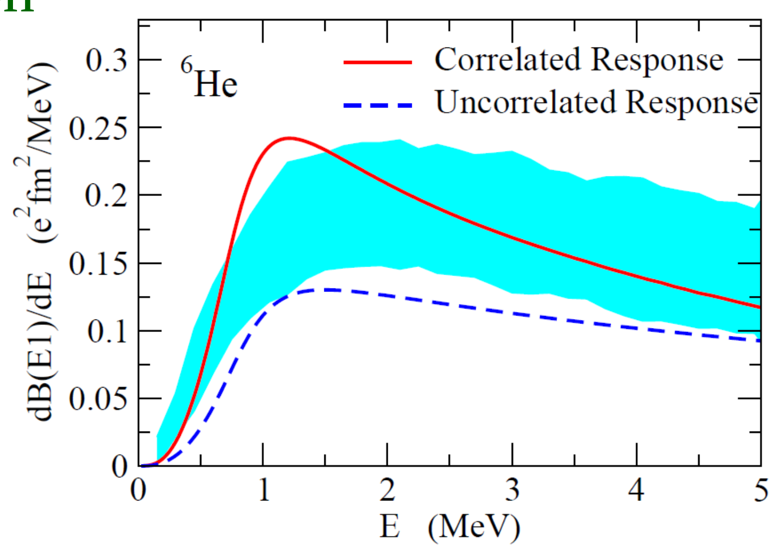
K.H. and H. Sagawa, PRC72('05)





di-neutron correlations

Dipole transition

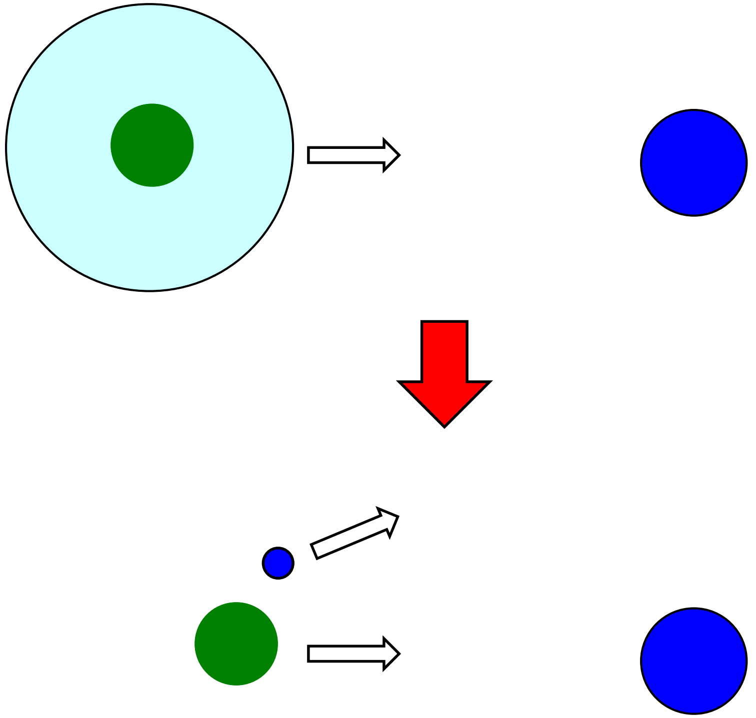


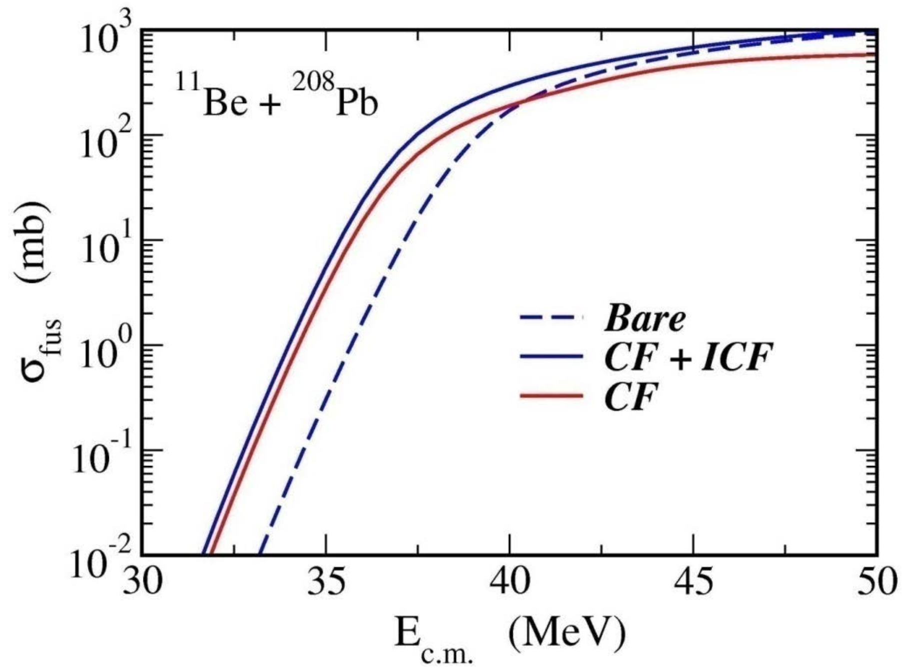
similarity to BCS-BEC

K.H., H. Sagawa,
P. Schuck, J. Carbonel,
PRL99('07) 022506.

K.H., H. Sagawa, T. Nakamura,
S. Shimoura, PRC80('09)

Fusion of halo nuclei



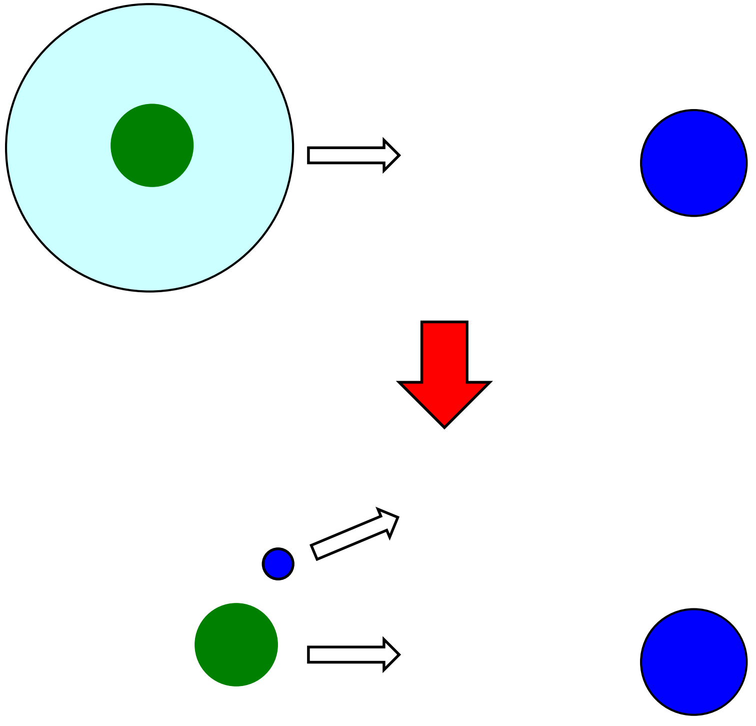


K. H., A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00)

1. Lowering of potential barrier
   due to a halo structure
   ⟶ enhancement
2. effect of breakup
3. effect of transfer

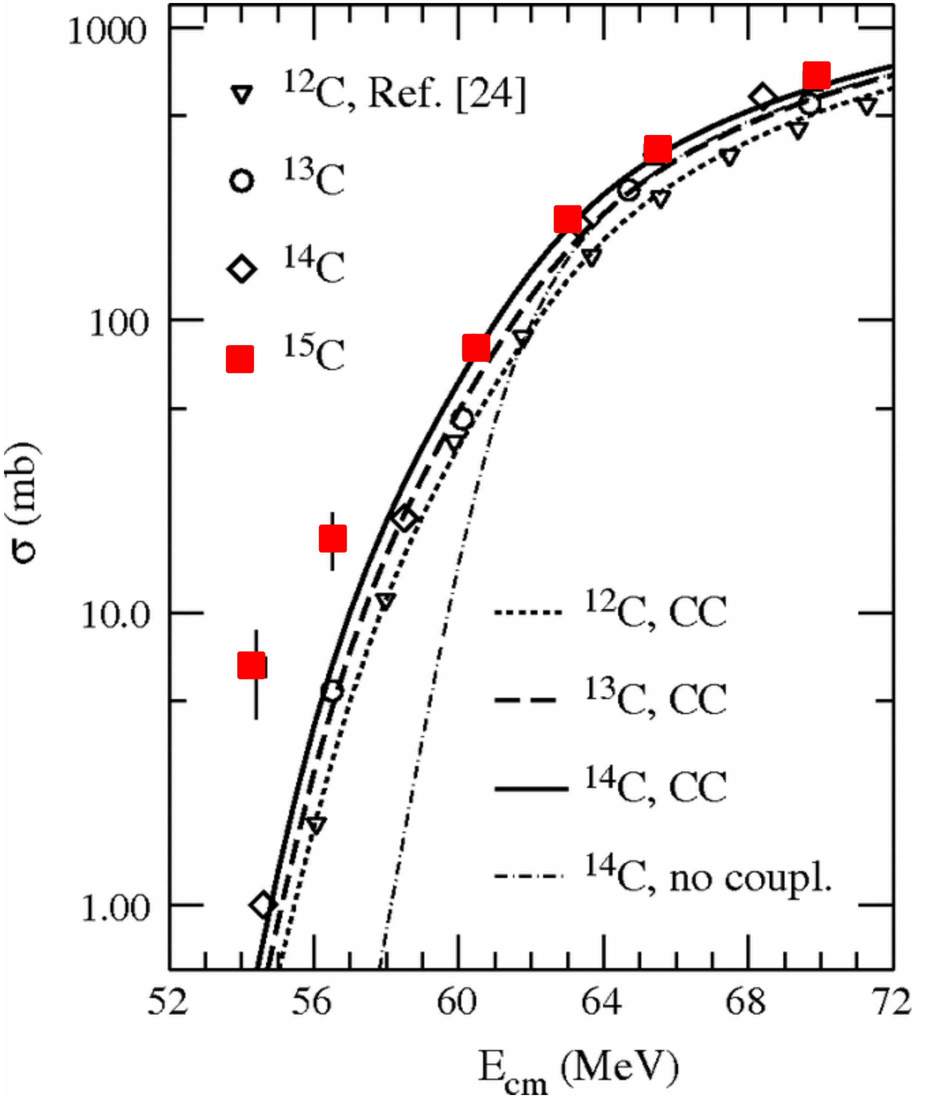
Review of H.I. fusion: K.H. and N. Takigawa, PTP128 ('12) 1061.

Fusion of halo nuclei



1. Lowering of potential barrier
   due to a halo structure
   ⟶ enhancement
2. effect of breakup
3. effect of transfer

$^{12,13,14,15}C + ^{232}Th$

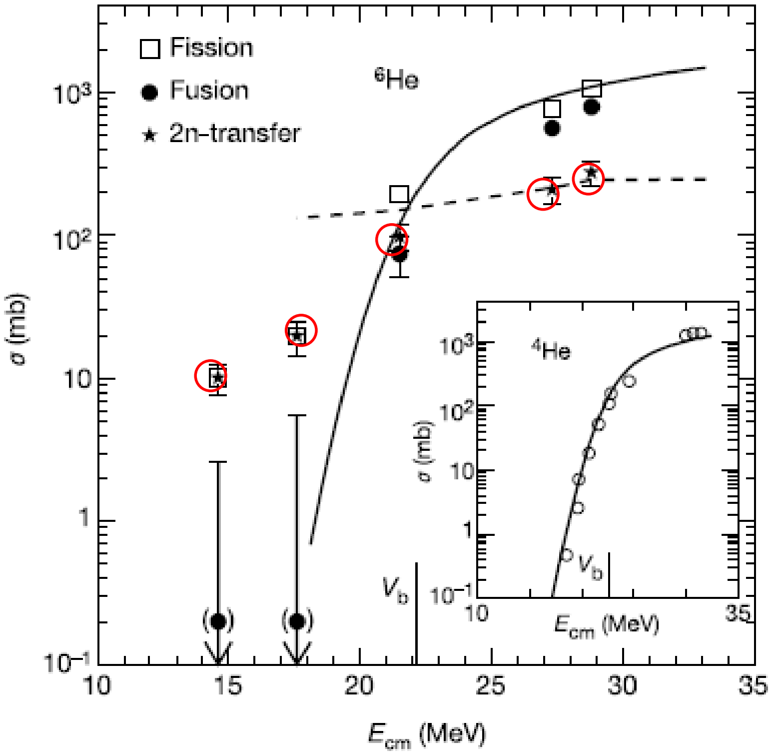


M. Alcorta et al., PRL106('11)

Review of H.I. fusion: K.H. and N. Takigawa, PTP128 ('12) 1061.

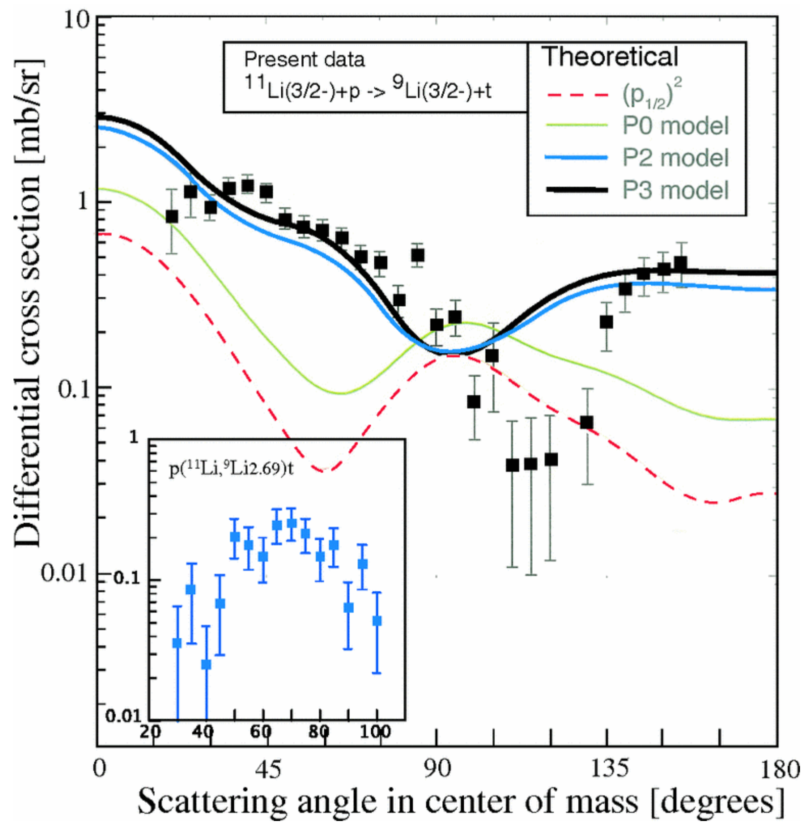
Two-neutron transfer reactions: pairing correlations

$^{6}He + ^{238}U$

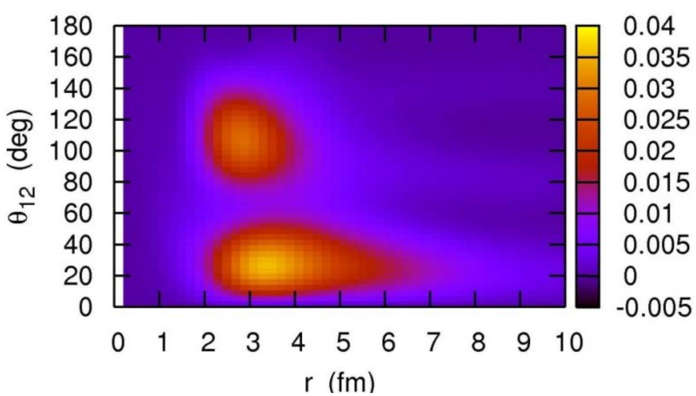


R. Raabe et al., Nature 431 (‘04)823

$^{1}H(^{11}Li,^{9}Li)^{3}H$



I. Tanihata et al., PRL100(‘08)192502

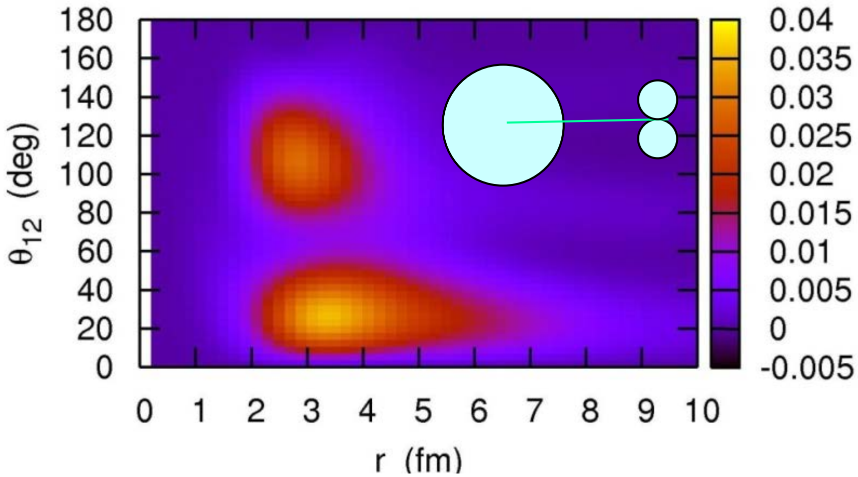


✓reaction mechanics?

✓role of unbound intermediate states?

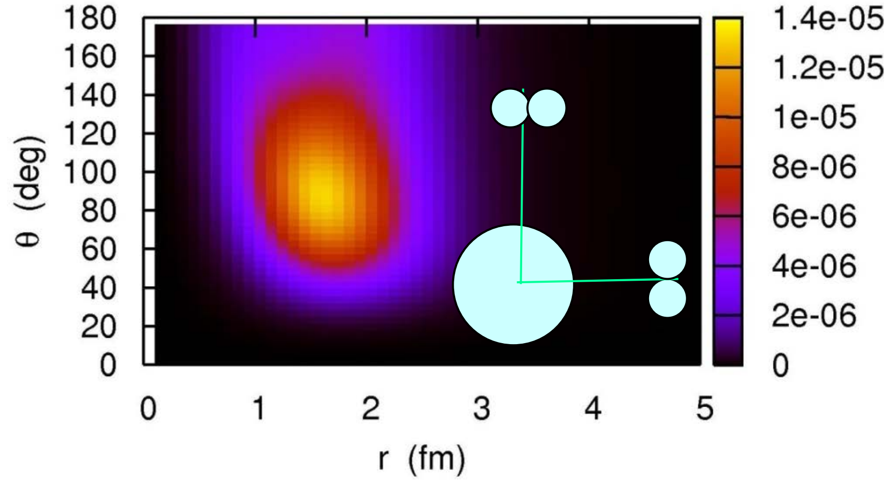
Future perspectives (nn correlations):

$^{6}He = {}^{4}He$ + "dineutron"



K.H. and H. Sagawa, PRC72('05)

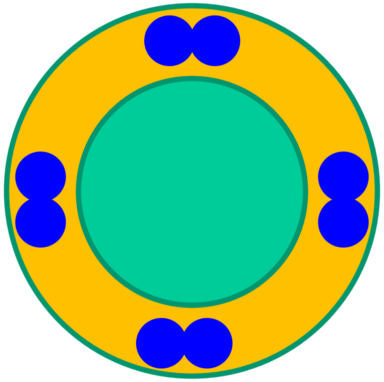
$^{8}He = {}^{4}He$ + two "dineutrons"



HFB calculation

K.H., N. Takahashi, and H. Sagawa, PRC77('08)

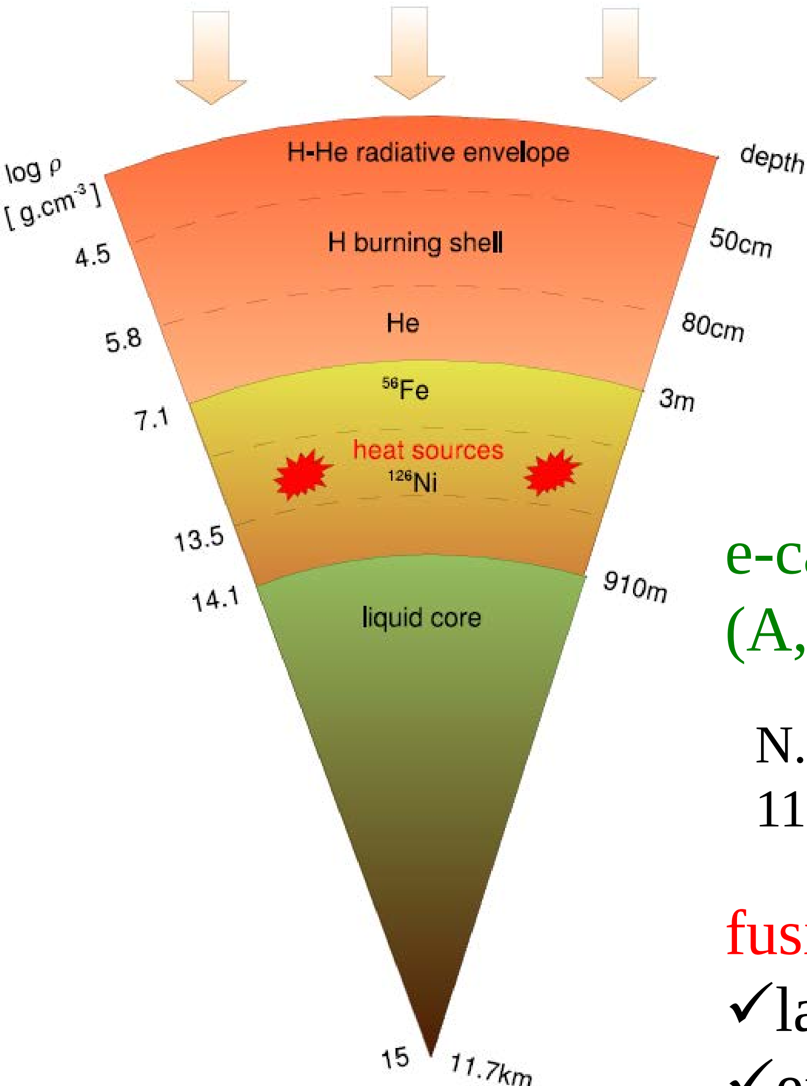
heavier neutron-rich nuclei



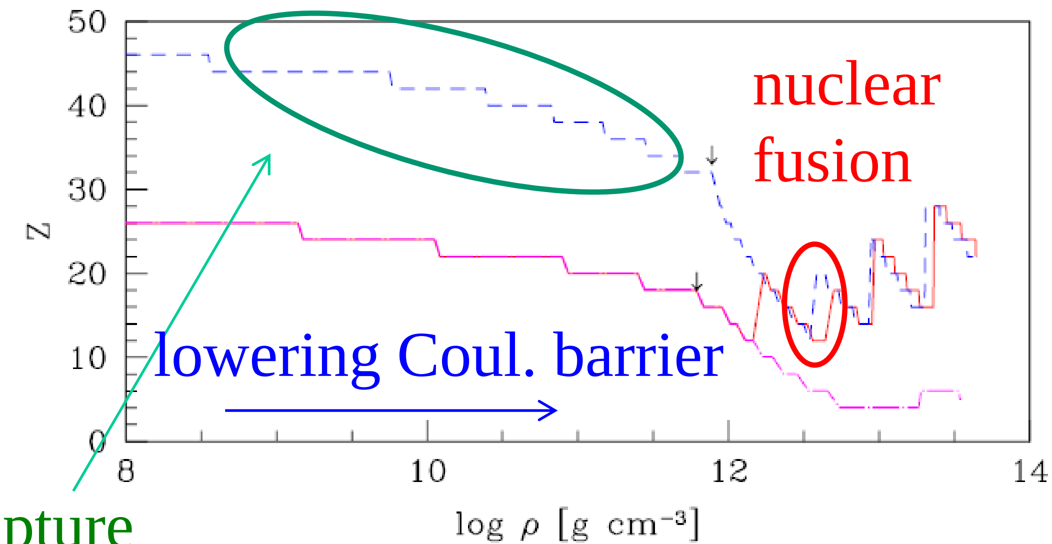
surface dineutron condensation in neutron skin??

Fusion in neutron stars

accretion



^{34}Ne + ^{34}Ne etc.



e-capture

$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$

N. Chamel and P. Haensel, Living Rev. Relativity, 11 (‘08) 10.

fusion between two neutron-rich nuclei

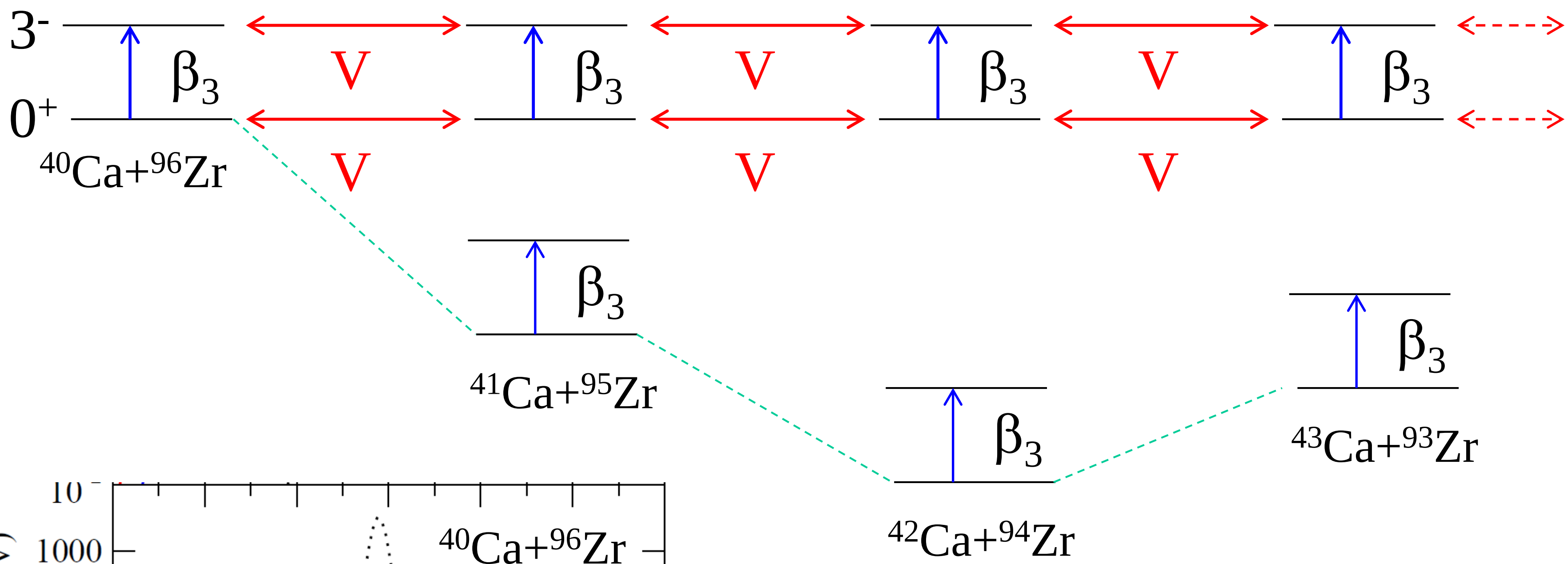
✓large uncertainty in pycnonuclear fusion

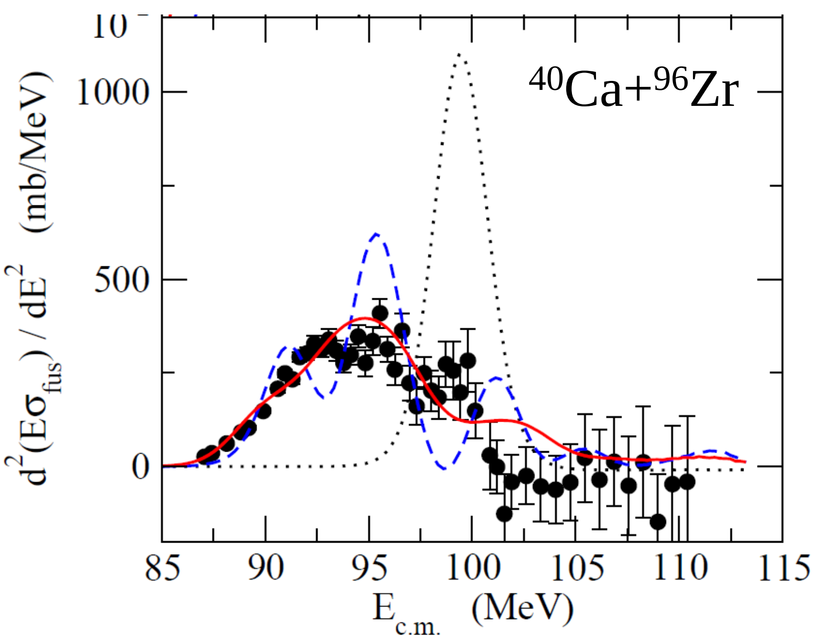
✓effect of large neutron skins?

✓information on nuclear EOS?

multi-neutron transfer reactions   cf. KISS project

new simple Coupled-channels model





$$\sigma_{\mathrm{fus}}(E) = \sum_i w_i \, \sigma_{\mathrm{CC}}(E + \lambda_i)$$

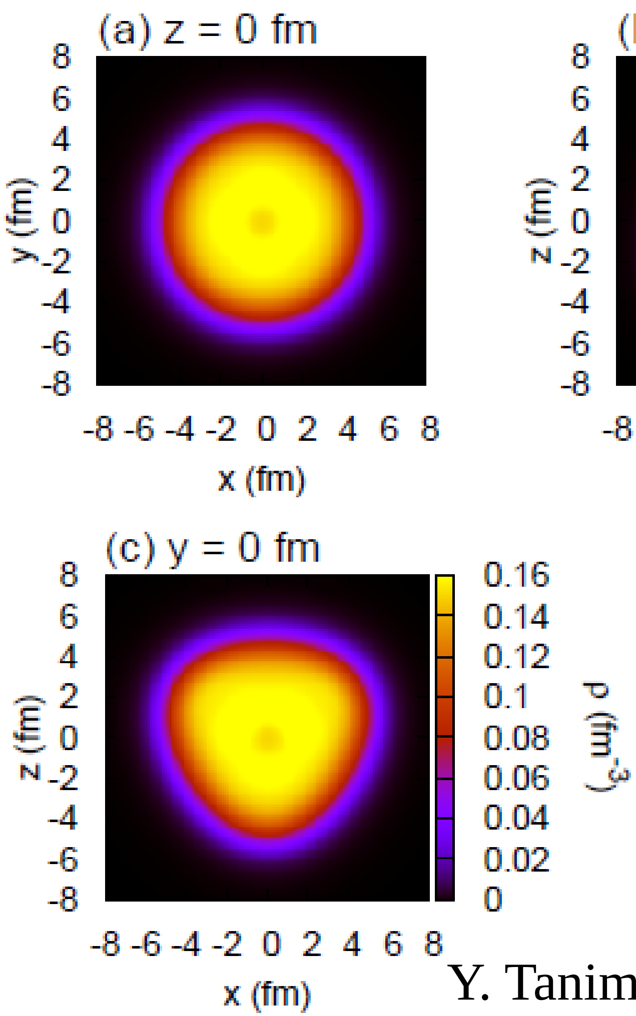
✓N. Sekine, master thesis (2012)

✓K.H., N. Sekine, and N. Rowely, unpublished (2012)

✓ Deformations

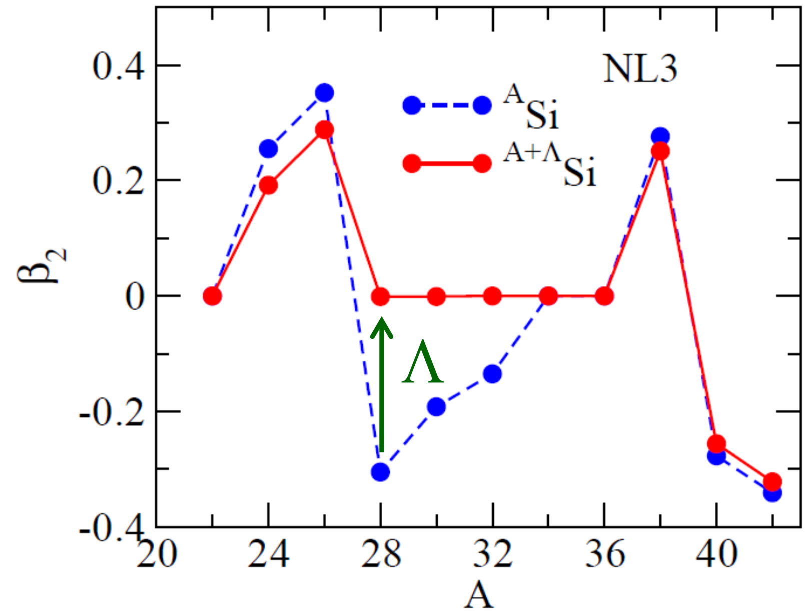
- RMF in 3D mesh

density of ^{80}Zr (tetrahedral def.)



Y. Tanimura, K.H., H.Z. Liang,
PTEP 2015 (‘15) 073D01

- deformation of hypernuclei



Myaing Thi Win and K.H.,
PRC78(‘08)054311

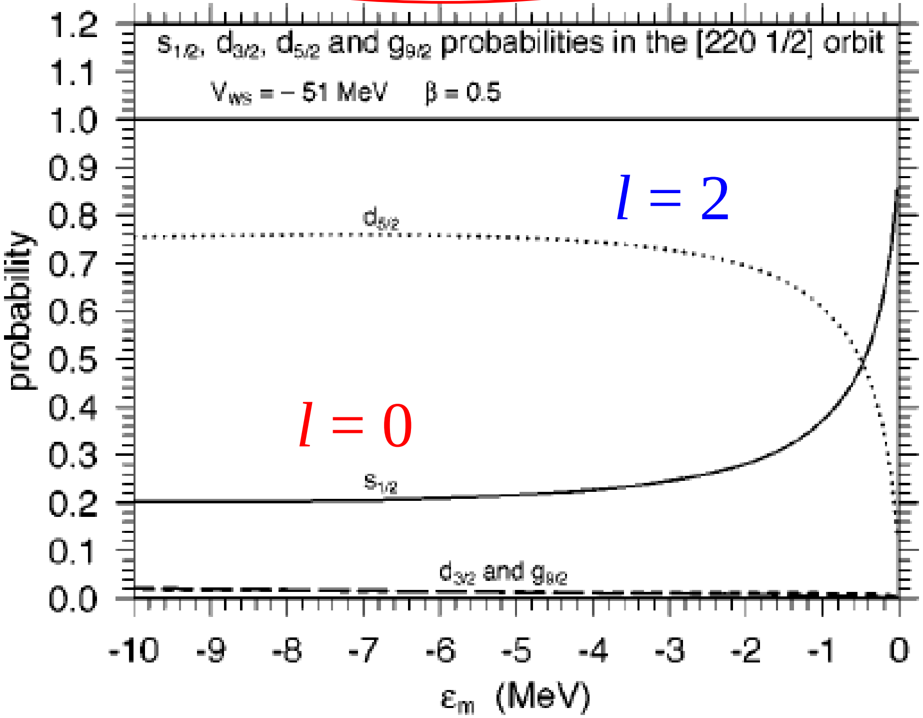
disappearance of nuclear deformation

deformed halo nuclei

halo: l = 0 or 1 only

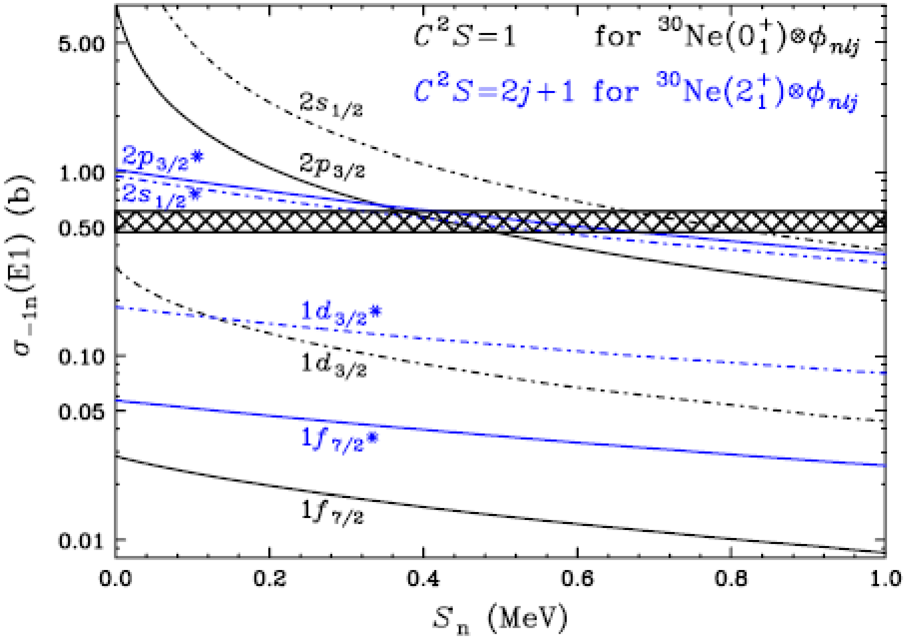
but in a deformed potential,

$$|d_{5/2}\rangle \rightarrow |d_{5/2}\rangle + |s_{1/2}\rangle + |g_{7/2}\rangle + \cdots$$
$$\rightarrow |s_{1/2}\rangle \quad (|\epsilon| \rightarrow 0)$$



I. Hamamoto, PRC69('04)041306(R)
(deformed Woods-Saxon)

large E1 prob. for ^{31}Ne



T. Nakamura et al., PRL103('09)

also large σ_{reac}

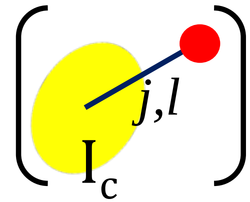
M.Takechi et al., PLB 707('12)

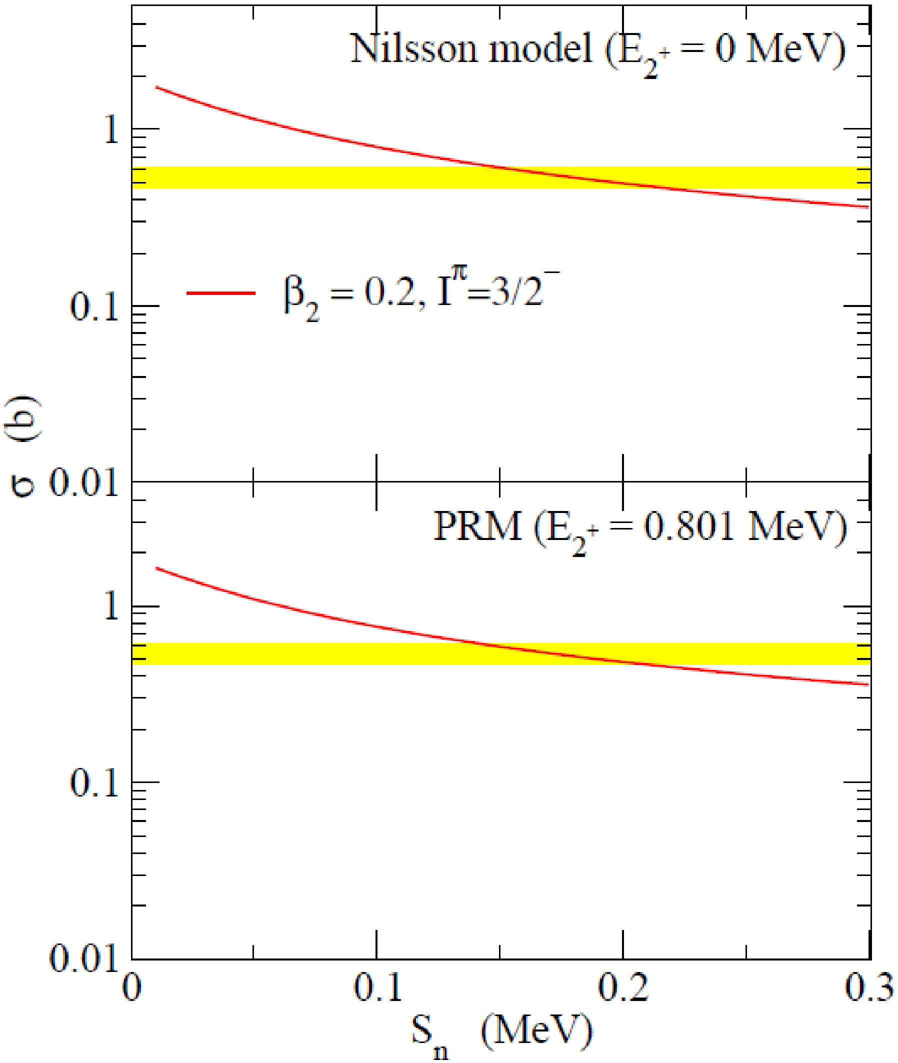
↓

deformed halo nucleus?

analysis with particle-rotor model (coupled-channels method)

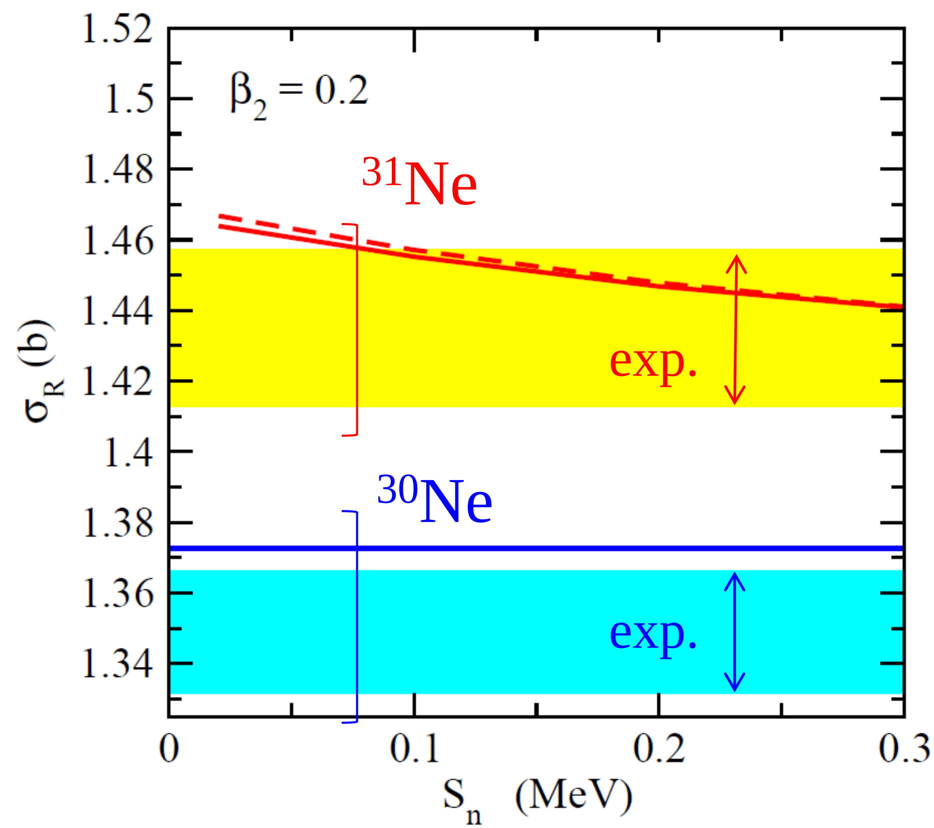
$$\Psi_{IM} = \sum_{I_c,j,l} \left[\quad \right]^{(IM)}$$





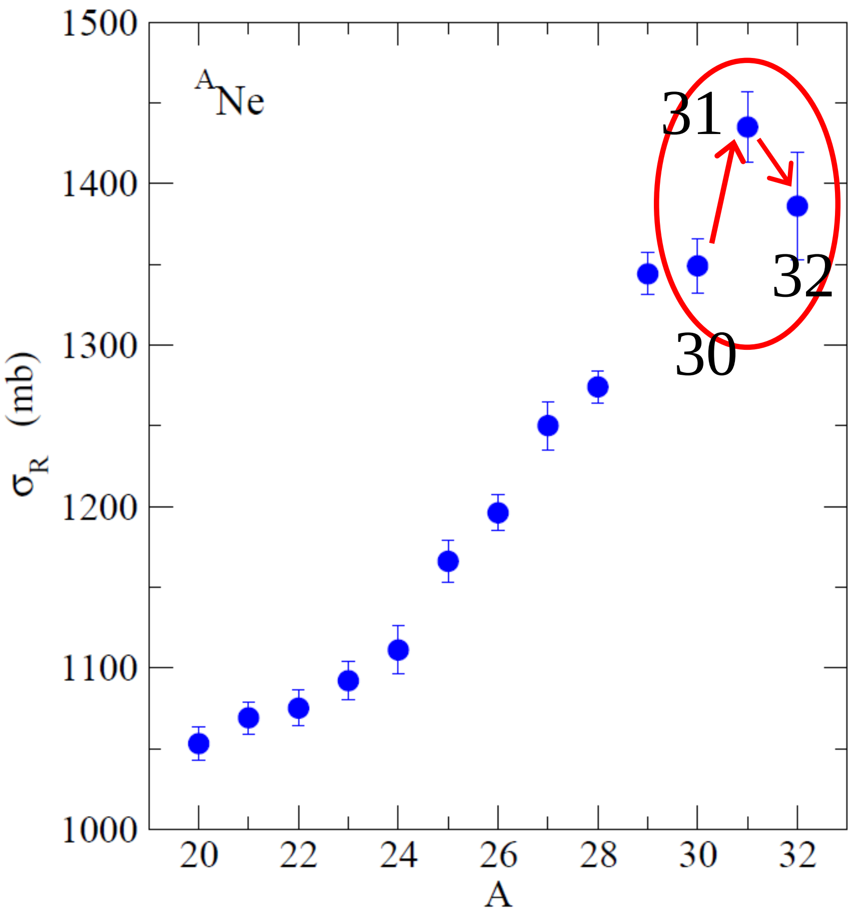
Y. Urata, K.H., and H. Sagawa, PRC83('11) 041303 (R)

consistent both with σ_{bu} and σ_R



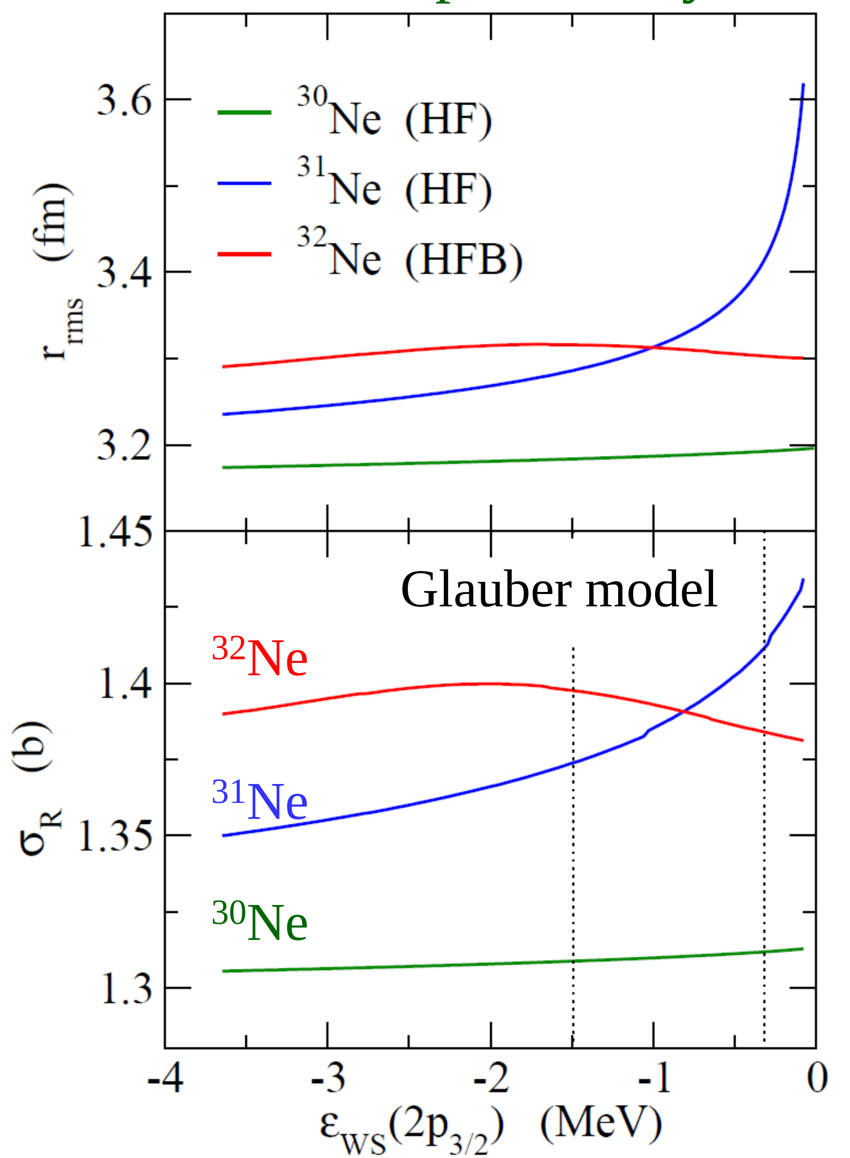
Y. Urata, K.H., and H. Sagawa, PRC86('12) 044613

Odd-even staggering in reaction cross sections



M.Takechi et al., PLB 707('12)

spherical symm.



K. H. and H. Sagawa, PRC84('11)

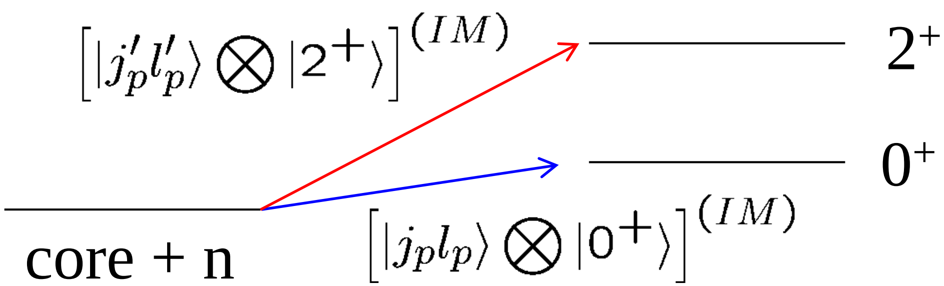
Future perspectives: deformed halo nuclei

✓Possibility of a heavy halo nucleus

what is the heaviest halo nuclues? cf. ^{127}Ru (Hamamoto, PRC85)

✓"Fine structure" in breakup/transfer reactions

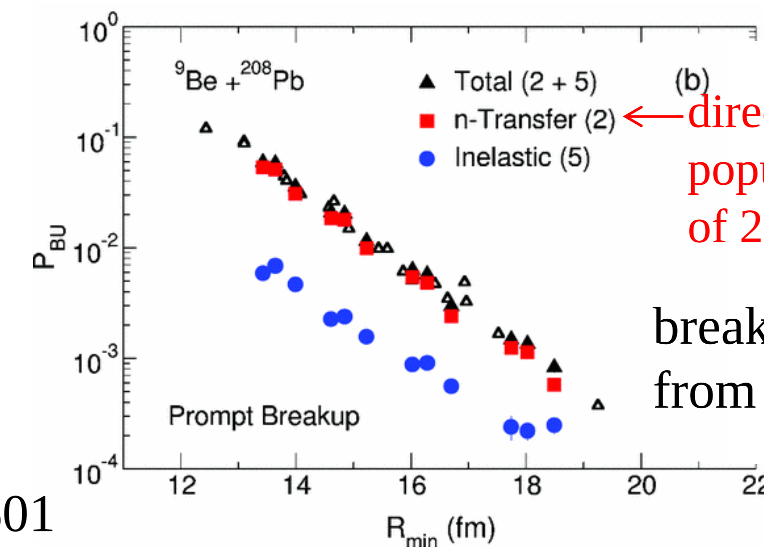
direct population of the 2^+ state after breakup/transfer



cf. proton decay

✓Influence on low-energy heavy-ion reactions (e.g., sub-barrier fusion)

interplay between
breakup/ transfer/ rotational
couplings

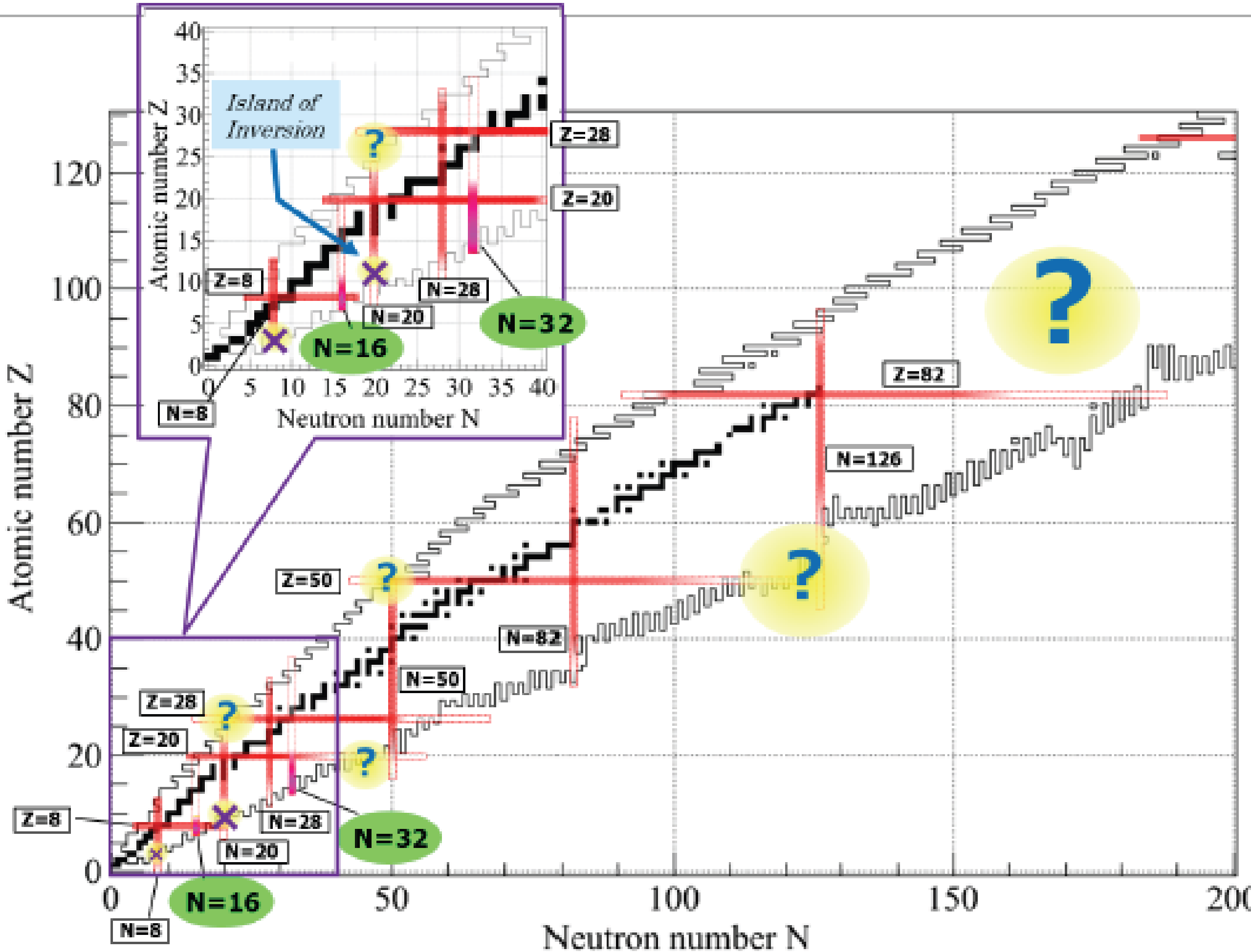


direct population of 2^+ in ^{8}Be

breakup from ^{8}Be*

R. Rafiei et al.,
PRC81('10)024601

✓ Single-particle motions and magic numbers



✓ disappearance of N=8, 20

✓ appearance of new magic # N=16,32,34

✓ new magic numbers in heavier n-rich nuclei?

(medium-) heavy nuclei: correlations

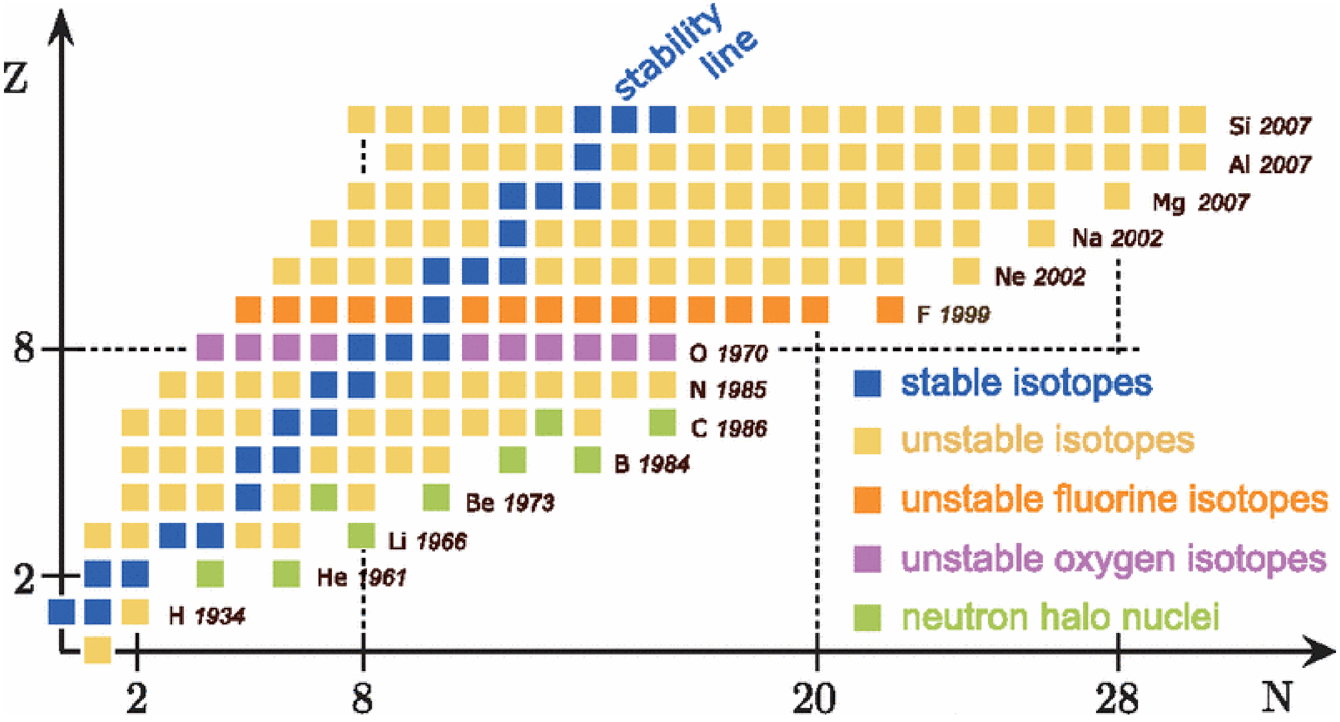
- pairing
- deformation
- collective motions

⇔ effects on shell evolution?

shell evolution in medium-heavy/heavy nuclei

⟵ self-consistent mean-field approach

✓ oxygen anomaly



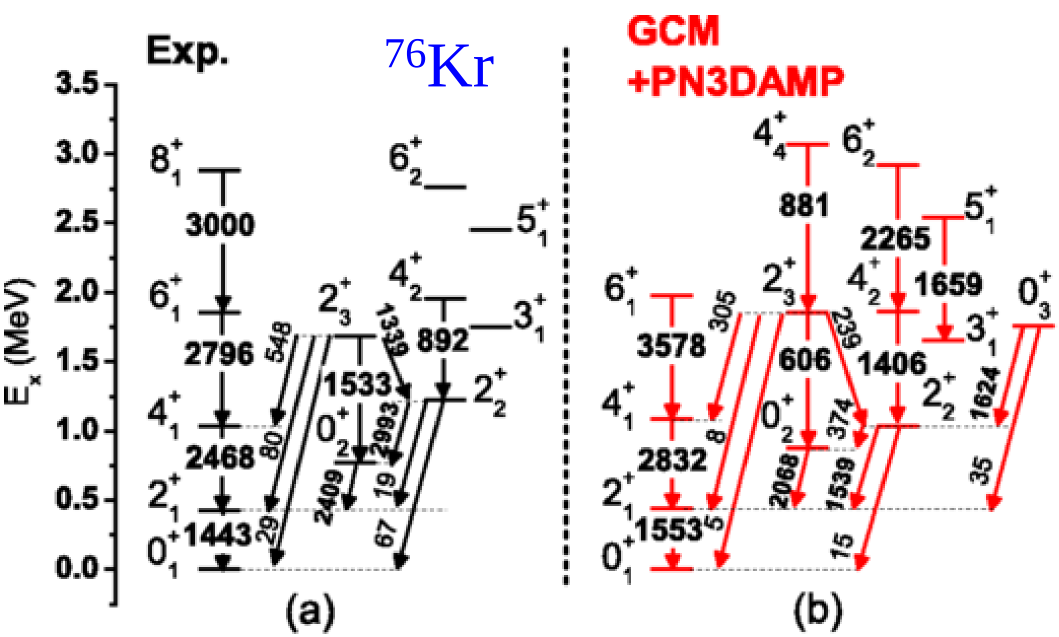
✓ three-body force
✓ tensor interaction

T. Otsuka et al.,
PRL95(‘05)232502
PRL105(‘10)032501

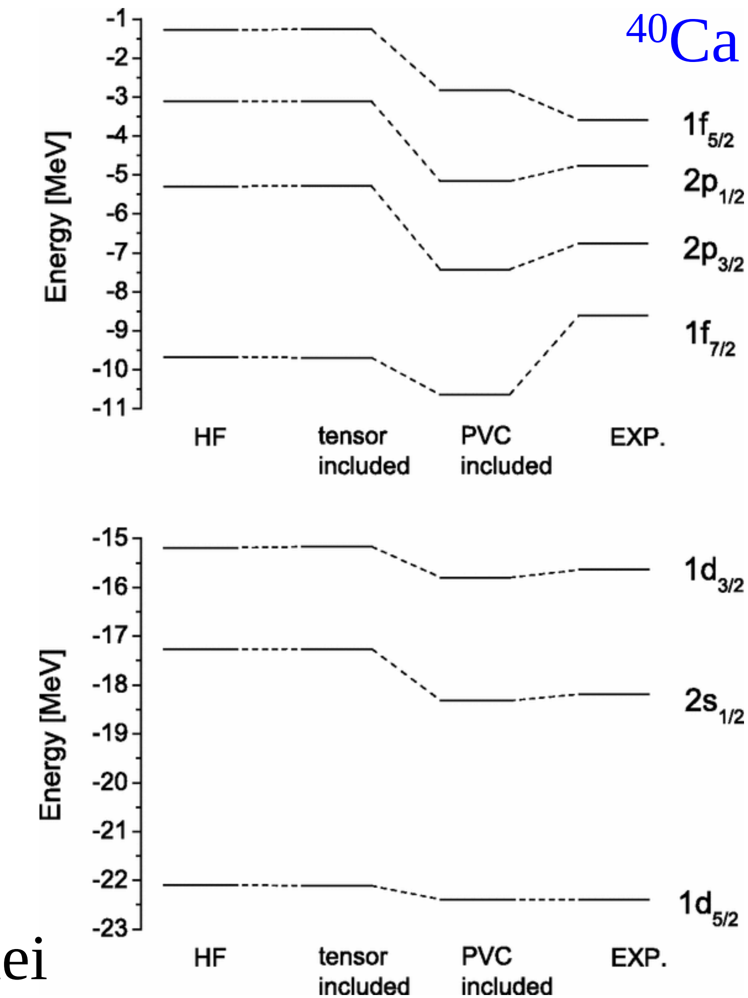
✓ correlations due to “beyond-mean-field-approximation”

- fluctuation of mean-field: generator coordinate method
- particle-vibration couplings

- beyond MF (GCM) calculations
- particle-vibration couplings



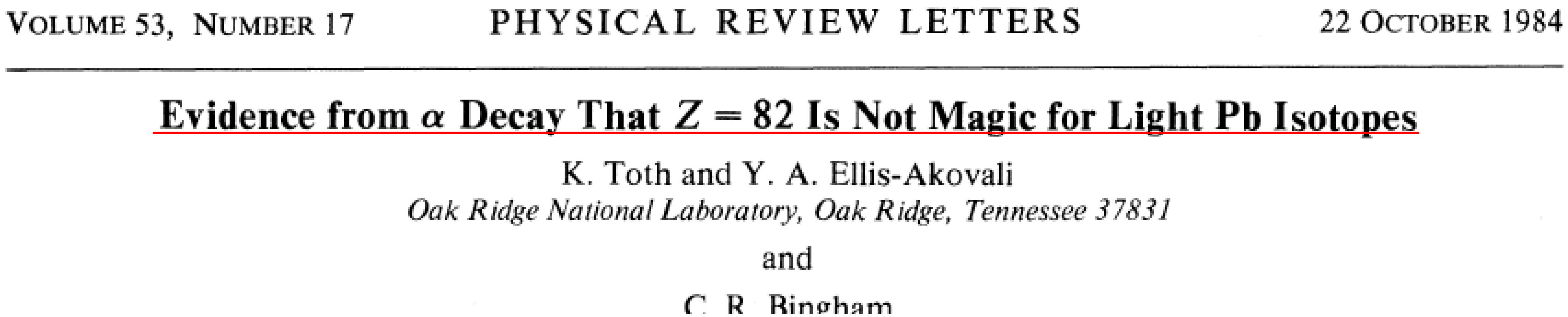
J.M. Yao, K.H. et al.,
PRC89 (‘14) 054306



G. Colo, H. Sagawa,
and P.F. Bortignon, PRC82(‘10)

✓ shell closures in heavy n-rich nuclei
✓ collective and s.p. motions

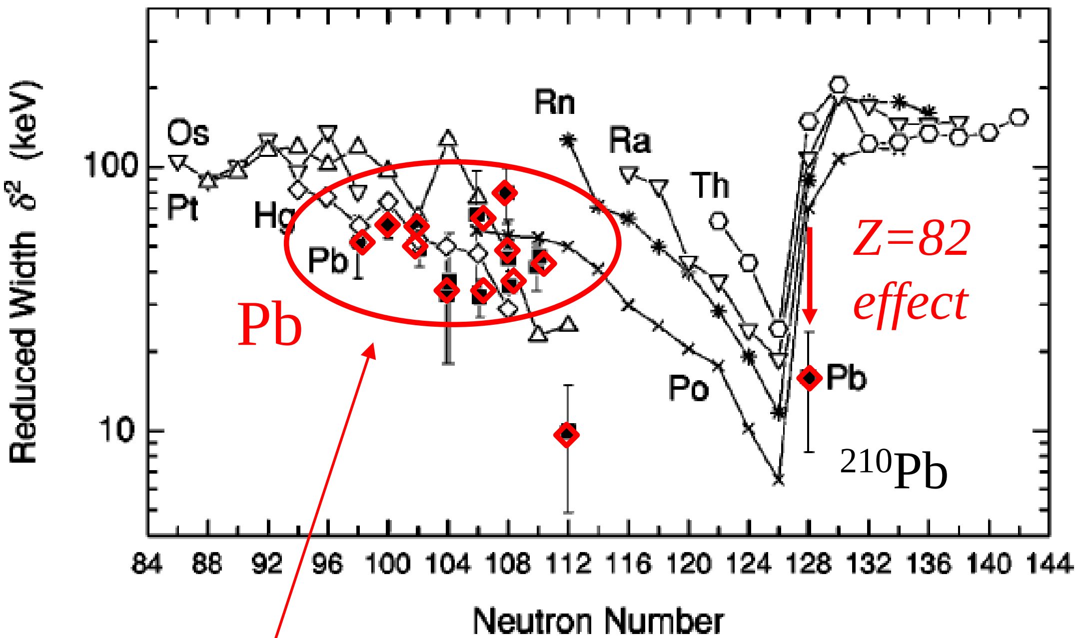
need high performance computing


VOLUME 53, NUMBER 17 PHYSICAL REVIEW LETTERS 22 OCTOBER 1984

Evidence from α Decay That Z = 82 Is Not Magic for Light Pb Isotopes

K. Toth and Y. A. Ellis-Akovali
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
and
C. R. Bingham

α-decay reduced width
(pre-formation factor)



disappearance of
Z=82 effect?

- ➢ disappearance of Z=82 in p-rich Pb isotopes?
- ➢ deformation in p-rich Po isotopes?
  (A.N. Adreyev et al., PRL110 ('13) 242502)

RIBF/ p-RIBF

N=82 in n-rich nuclei?

cf. H. Watanabe, PRL111('13)

a large shell gap at $^{128}_{46}Pd_{82}$

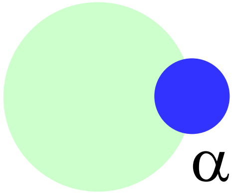
Z=82 in p-rich nuclei?

theory

alpha-decay theory   cf. SHE

α decays: as complex as fission

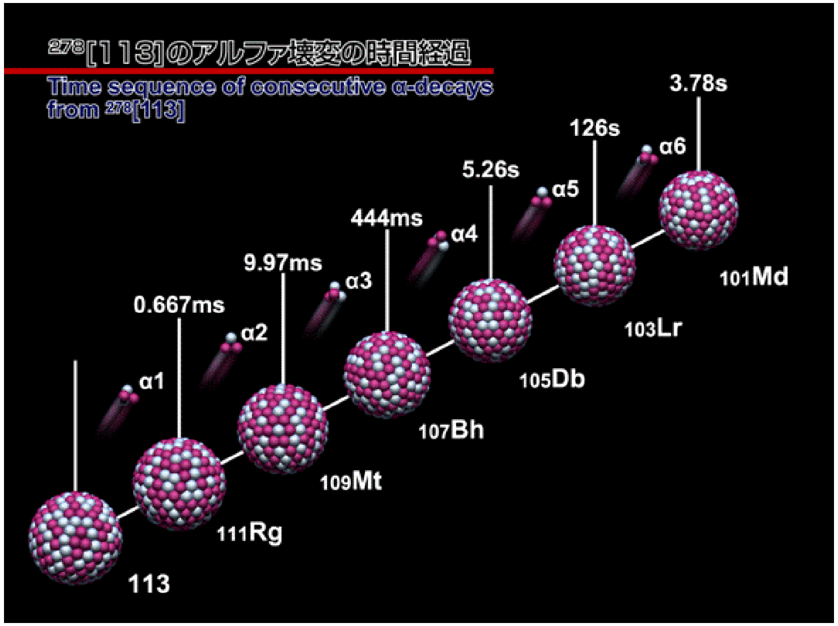
$$\Gamma_\alpha \sim S_\alpha \cdot P_{\text{tunnel}}$$



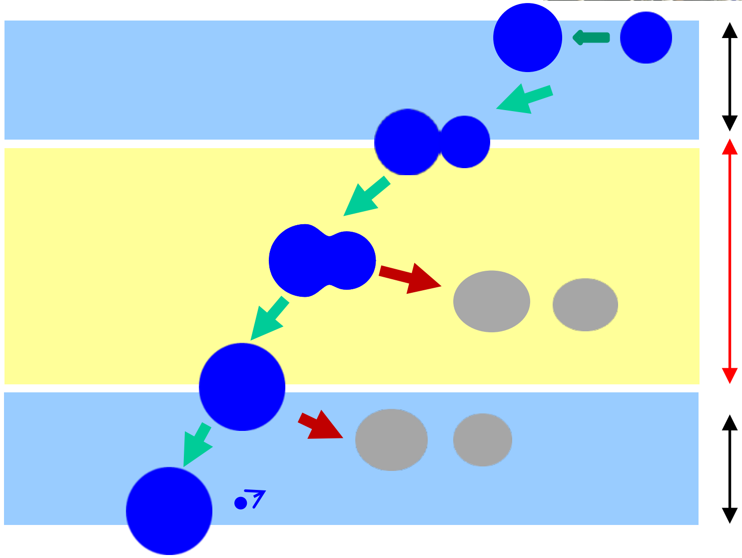
S_α ⟷ nuclear structure information

large ambiguities

- how to calculate S_α for n-rich and p-rich nuclei?
- clustering probability on the surface?
- α-daughter potential (especially inside)?



Super-heavy nuclei



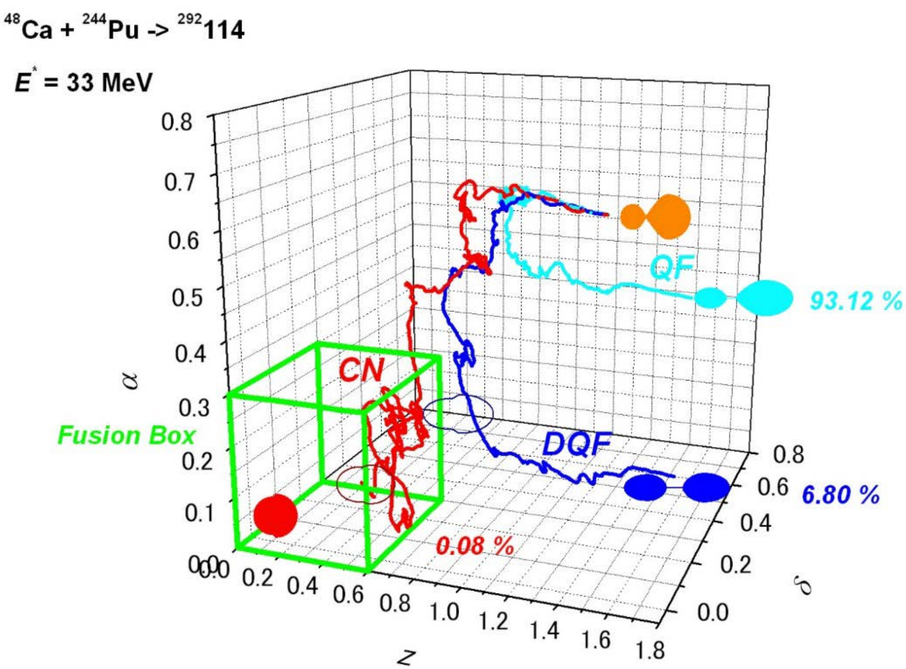
coupled-channels method

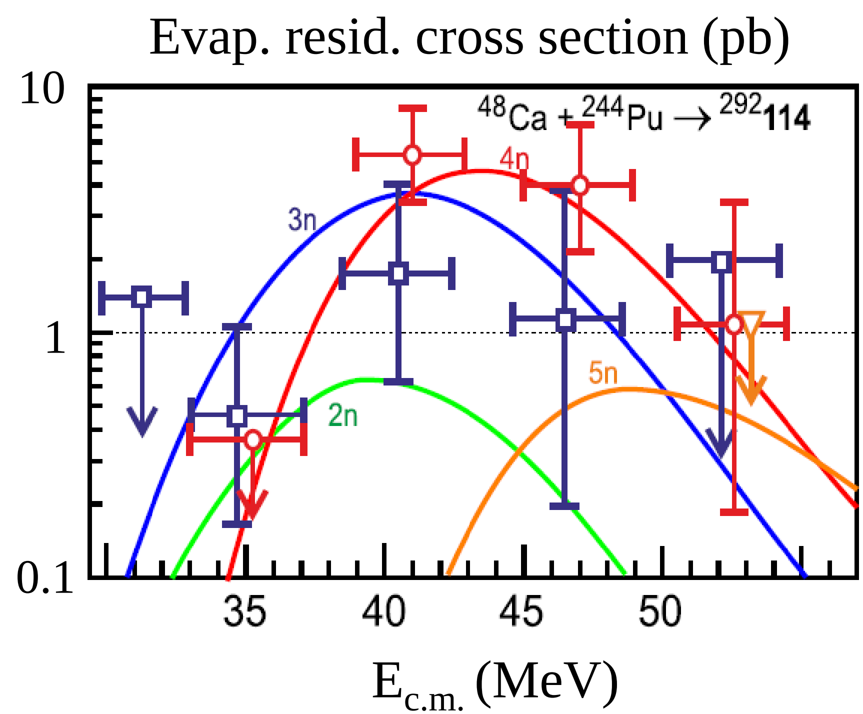
Langevin approach

V.I. Zagrebaev and W. Greiner, NPA944('15)257

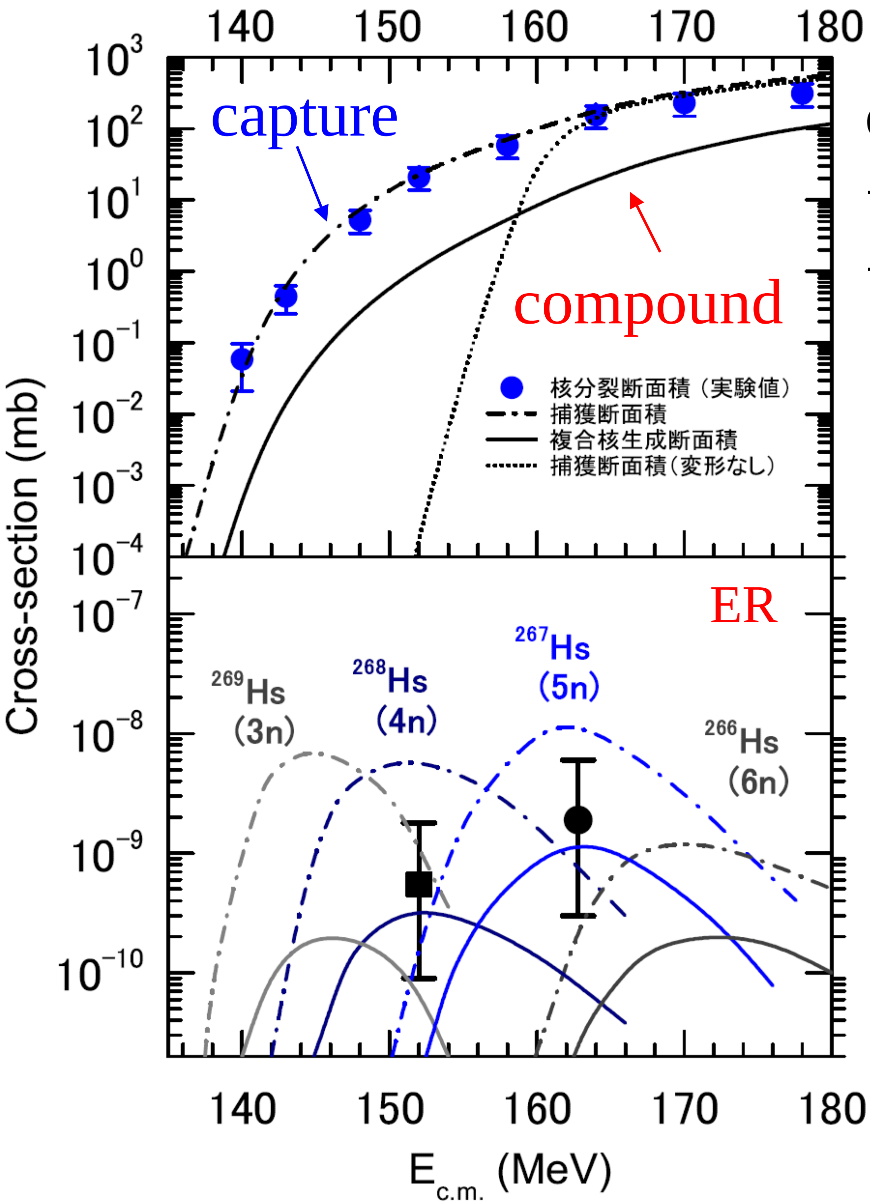
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

statistical model





^{34}S + ^{238}U



coupled-channels (entrance) K.H.
+ Langevin (touching to CN) Aritomo
+ statistical model Aritomo

Butsuri (Oct., 2013)

◆◆◆◆ 解説 ◆◆◆◆

重イオン核融合反応と超重元素

萩野浩一
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有友嘉浩
東京工業大学原子炉工学研究所
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自然界に存在する元素で最も重いものはこれまで測定された範囲ではプルトニウム（Pu）である．この元素は原子番号94を持ち，ウラン鉱石の中にわずかに含まれる．これより大きい原子番号の元素，例えば，96番元素のキュリウム（Cm）や100番元素のフェルミウム（Fm）は人工的には作れるが，自然界には存在しない．これは何故だろうか？　どのような機構で最も重い元素の原子番号が決まっているのだろうか？

させて大きな原子核（複合核）を作る反応である（右下図）．しかし，超重核領域では，この複合核が生成されること自体が稀である．この領域では，接触した二つの原子核が変形して融合核を形作る前に強いクーロン斥力により再び分離してしまうという準核分裂が起きやすいためである．更に，できた複合核は圧倒的な確率で核分裂により崩壊する．寿命がある程度長い元素ができたことを確認するには，中性子などの放出

—Keywords—

核融合・複合核：
2つの原子核が融合して1つの原子核になることを核融合と呼び，融合してできた核を複合核と呼ぶ．

殻構造・安定の島：
原子の中で電子軌道が殻構造を持ち，最外殻が満たされる（閉殻）と化学的に安定な原子（不活性ガス）になるのと同様に，原子核の中での陽子や中性子のエネルギー準位にも殻構造があり

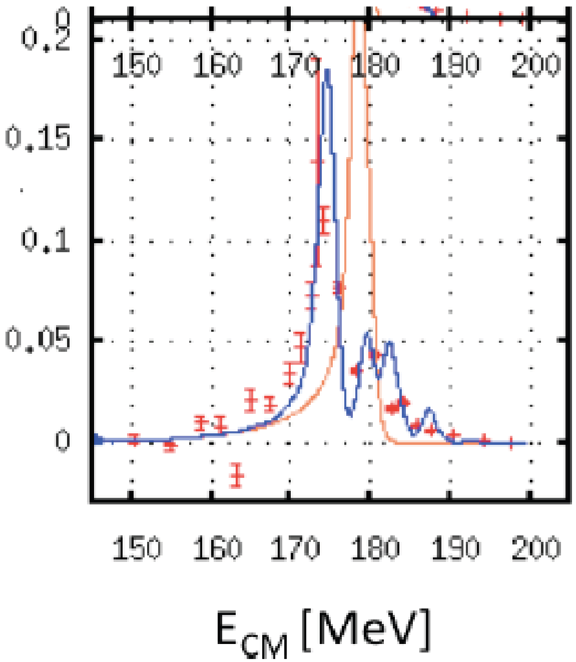
Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85(’12)044614 towards the island of stability

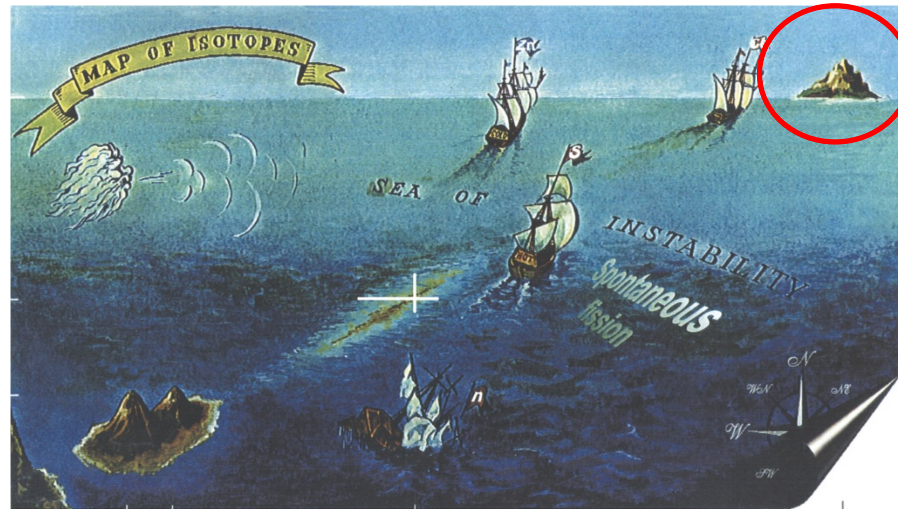
neutron-rich beams?

(i) Entrance

$^{48}Ca+^{208}Pb$

barrier distribution





- ✓ Quasi-elastic barrier distribution with GARIS (Y. Tanaka, K. Morita, 2015)
- ✓ C.C. calculation: CCFULL (K.H. et al., CPC123('99)143)
- ✓ theory: K.H. and N. Rowley, PRC69('04)054610

(ii) Langevin

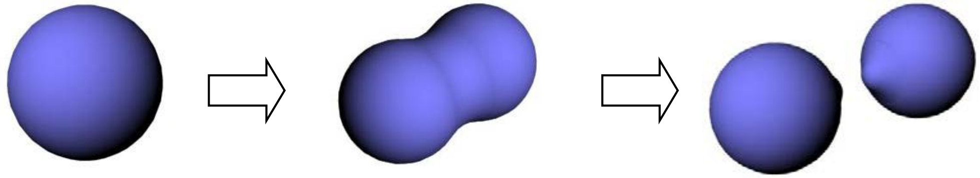
combination to n-evaporation

(iii) statistical model

decay dynamics of hot n-rich nuclei

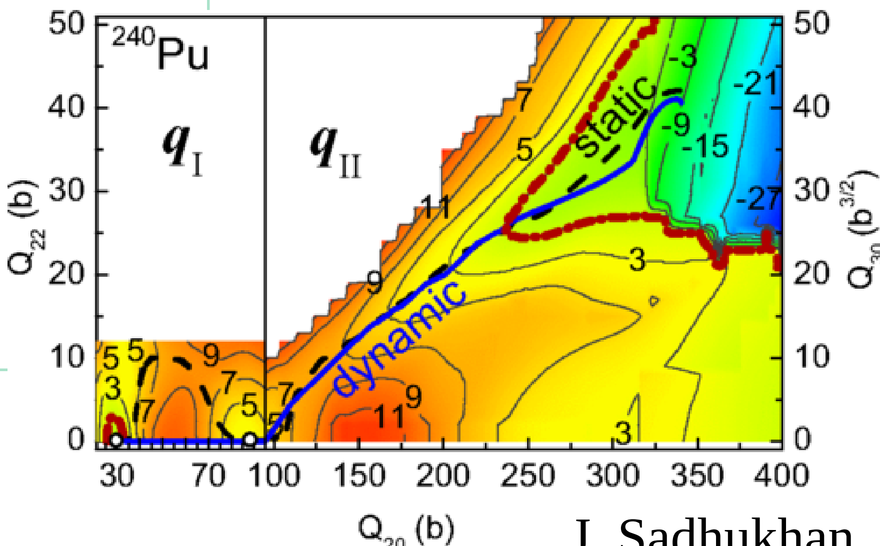
- ➢quantal theory for DIC? cf. multi-nucleon transfer
- ➢nuclear friction?

Fission



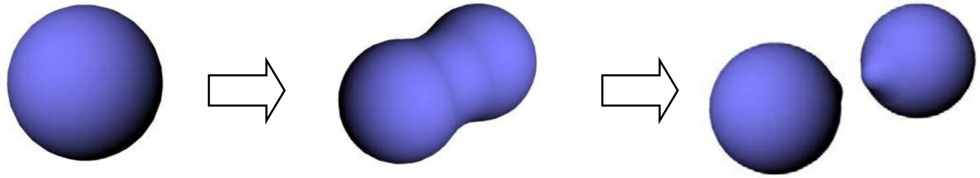
still a very challenging problem for nuclear theory

	Time-indep. approach	Time-dep. approach
Induced fission	✓Bohr-Wheeler	✓Langevin-type ✓Discrete basis (Bertsch)
Spontaneous fission	✓PES+Mass+WKB	✓Im.-time TDHF (Negele) ✓Time-dep. Hill-Wheeler (Goutte et al.) ✓TDHF (after the barrier)



J. Sadhukhan, W. Nazarewicz, N. Schunck, PRC93(‘16)011304(R)

Fission



still a very challenging problem for nuclear theory

	Time-indep. approach	**Time-dep. approach**
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Spontaneous fission	✓PES+Mass+WKB	✓Im.-time TDHF (Negele) ✓Time-dep. Hill-Wheeler (Goutte et al.) ✓TDHF (after barrier)

issues:

- which degrees of freedom? (time-indep. approaches)
- how to deal with many-body tunneling? (time-dep. approaches)

Other future theoretical issues:

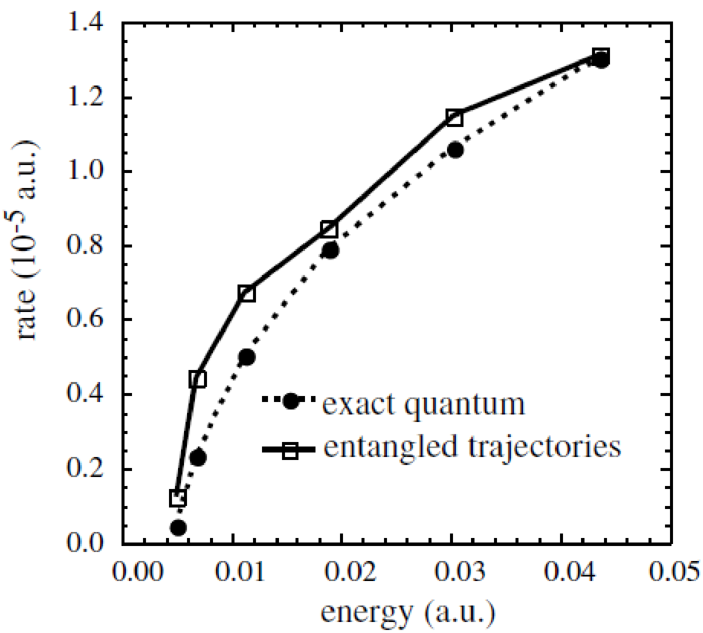
From phenomenological models to more microscopic models

- C.C. with microscopic inputs c.f. J.M. Yao and K.H., PRC91('15)
- DFT for spontaneous fission
- TDHF approach ←

➢ "Beyond mean-field" approximations

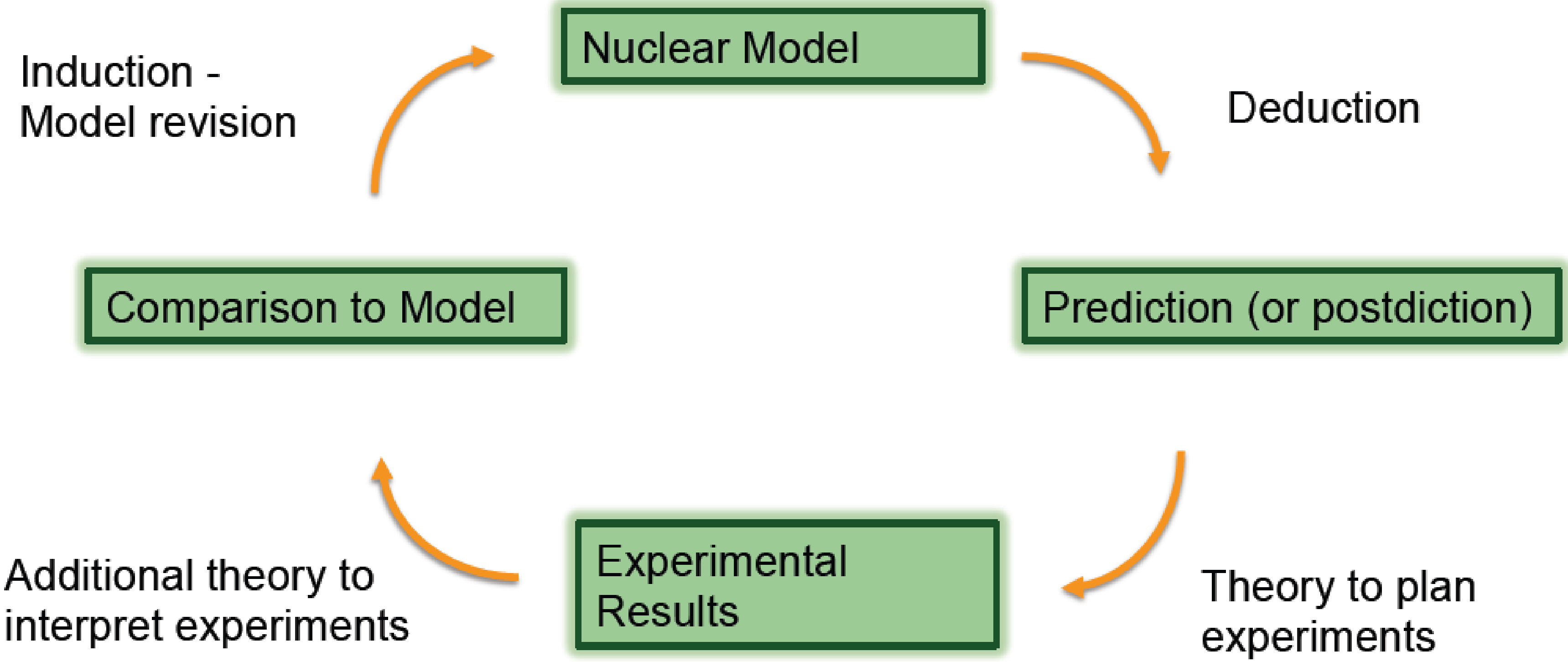
Full time-dependent GCM? $|\Psi(t)\rangle = \int dq\, f(q,t)|\Phi_q(t)\rangle$

→ many-body tunneling



cf. Quantum Chemistry
"Quantum tunneling using entangled classical trajectories"
A. Donoso and C.C. Martens,
PRL87 ('01) 223202

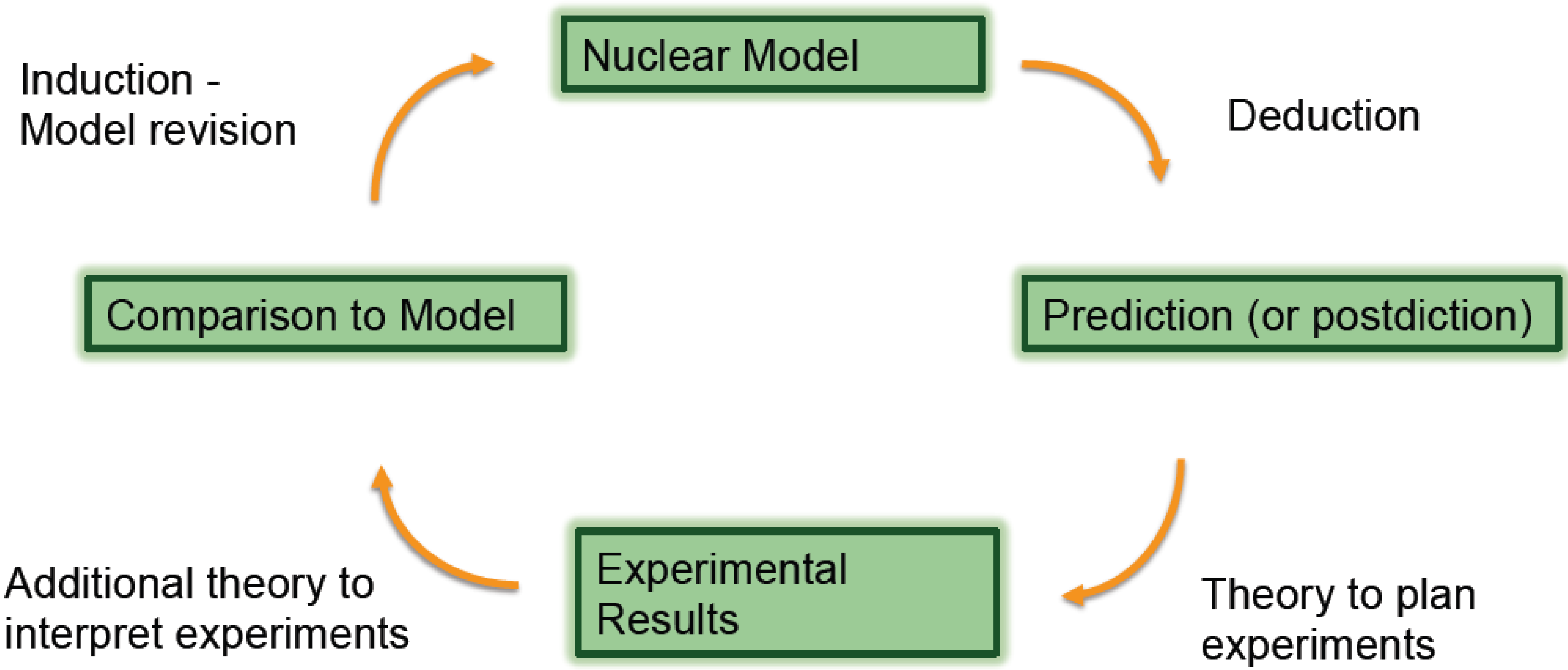
✓ Theory-experiment couplings



slide: Brad Sherrill

all the ingedients are important

✓ Theory-experiment couplings



slide: Brad Sherrill

cf. Three types of theoretician (Uesaka-san)

i) Totally independent to experiments

ii) those who make calculations for experimentalists (useful, but…)

iii) those who promote mutual developments between theo. and expt.

my personal theory-experiment couplings

PHYSICAL REVIEW C VOLUME 55, NUMBER 1 JANUARY 1997

Validity of the linear coupling approximation in heavy-ion fusion reactions at sub-barrier energies

K. Hagino* and N. Takigawa
Department of Physics, Tohoku University, Sendai 980-77, Japan

M. Dasgupta, D. J. Hinde, and J. R. Leigh

VOLUME 82, NUMBER 7 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1999

Fusion versus Breakup: Observation of Large Fusion Suppression for ^{9}Be + ^{208}Pb

M. Dasgupta,[1] D. J. Hinde,[1] R. D. Butt,[1] R. M. Anjos,[2] A. C. Berriman,[1] N. Carlin,[3] P. R. S. Gomes,[2] C. R. Morton,[1] J. O. Newton,[1] A. Szanto de Toledo,[3] and K. Hagino[4]

PHYSICAL REVIEW C **86**, 041307(R) (2012)

Double isobaric analog of ^{11}Li in ^{11}B

R. J. Charity,[1] L. G. Sobotka,[1] K. Hagino,[2] D. Bazin,[3] M. A. Famiano,[4] A. Gade,[3] S. Hudan,[5] S. A. Komarov,[1] Jenny Lee,[3] S. P. Lobastov,[3] S. M. Lukyanov,[3] W. G. Lynch,[3] C. Metelko,[5] M. Mocko,[3] A. M. Rogers,[3] H. Sagawa,[6,7] A. Sanetullaev,[3] M. B. Tsang,[3] M. S. Wallace,[3] M. J. van Goethem,[8] and A. H. Wuosmaa[4]

35 joint papers with experimentalists / 152 original papers (1994-2016)

29: H.I. subbarrier fusion reactions   2: hypernuclei

2: neutron-rich nuclei

2: proton decays

[FRIB theory alliance](#)

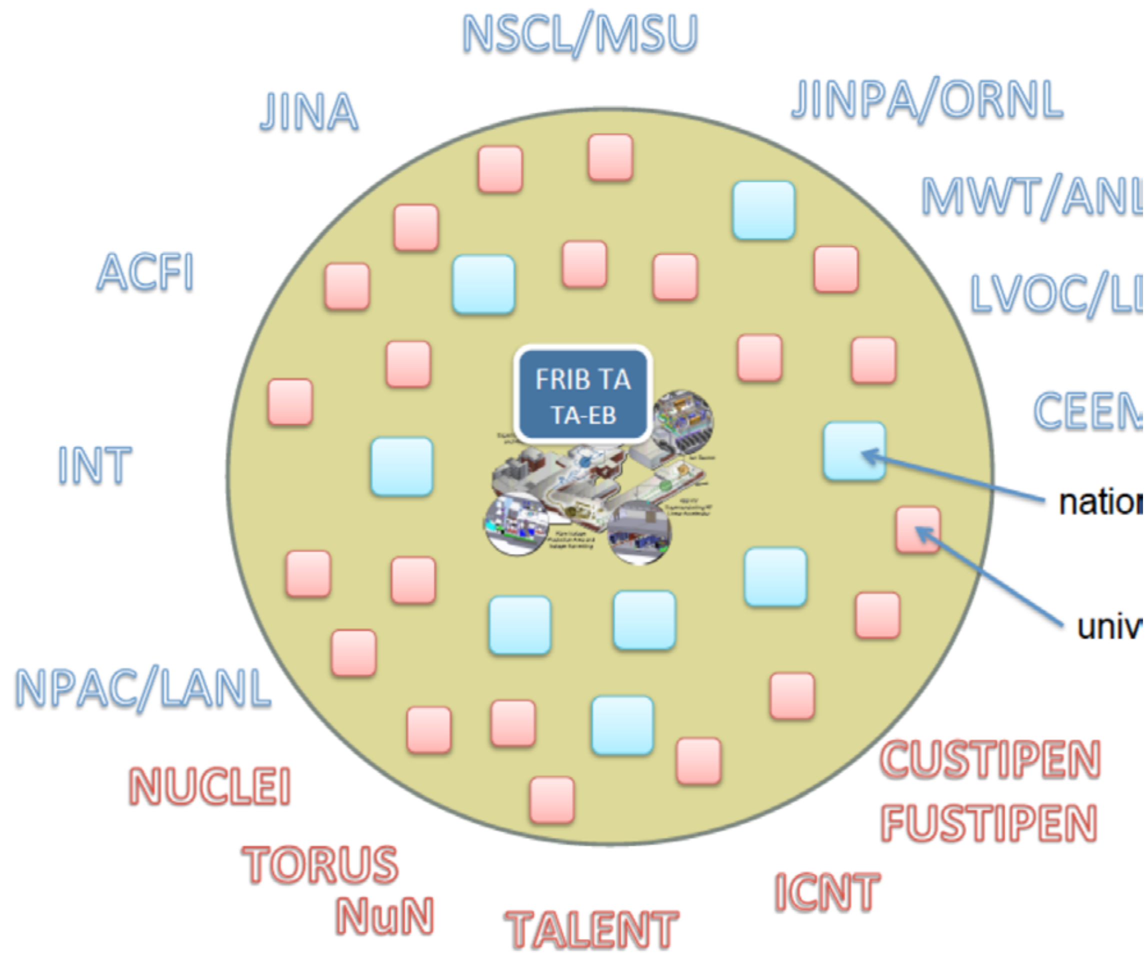
March 31-April 1 Inaugural meeting

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

"Enhancing theory efforts nationally"

FRIB theory alliance will:

- connect broadly across fields
- bring focus to those activities that are relevant
- identify and nurture the best talent
- take advantage of high performance computing



A possible snapshot for the FRIB theory alliance

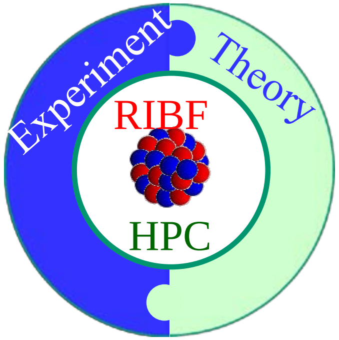
Summary: personal perspectives of the next 10-20 years

➢ Structure and reactions of n-rich medium-heavy and heavy nuclei

- ✓ halo and skin structures (deformation, surface dineutron condensation)
- ✓ decay dynamics (nuclei beyond the drip lines, excited states)
- ✓ influence on low-energy nuclear reactions (fusion, pair transfer)

➢ Shell evolution in heavy neutron-rich nuclei

- ✓ Stability of N=82, Z=82 shells
- ✓ theory of alpha decays
- ✓ extension of mean-field models with several correlations
- ✓ structure of SHE

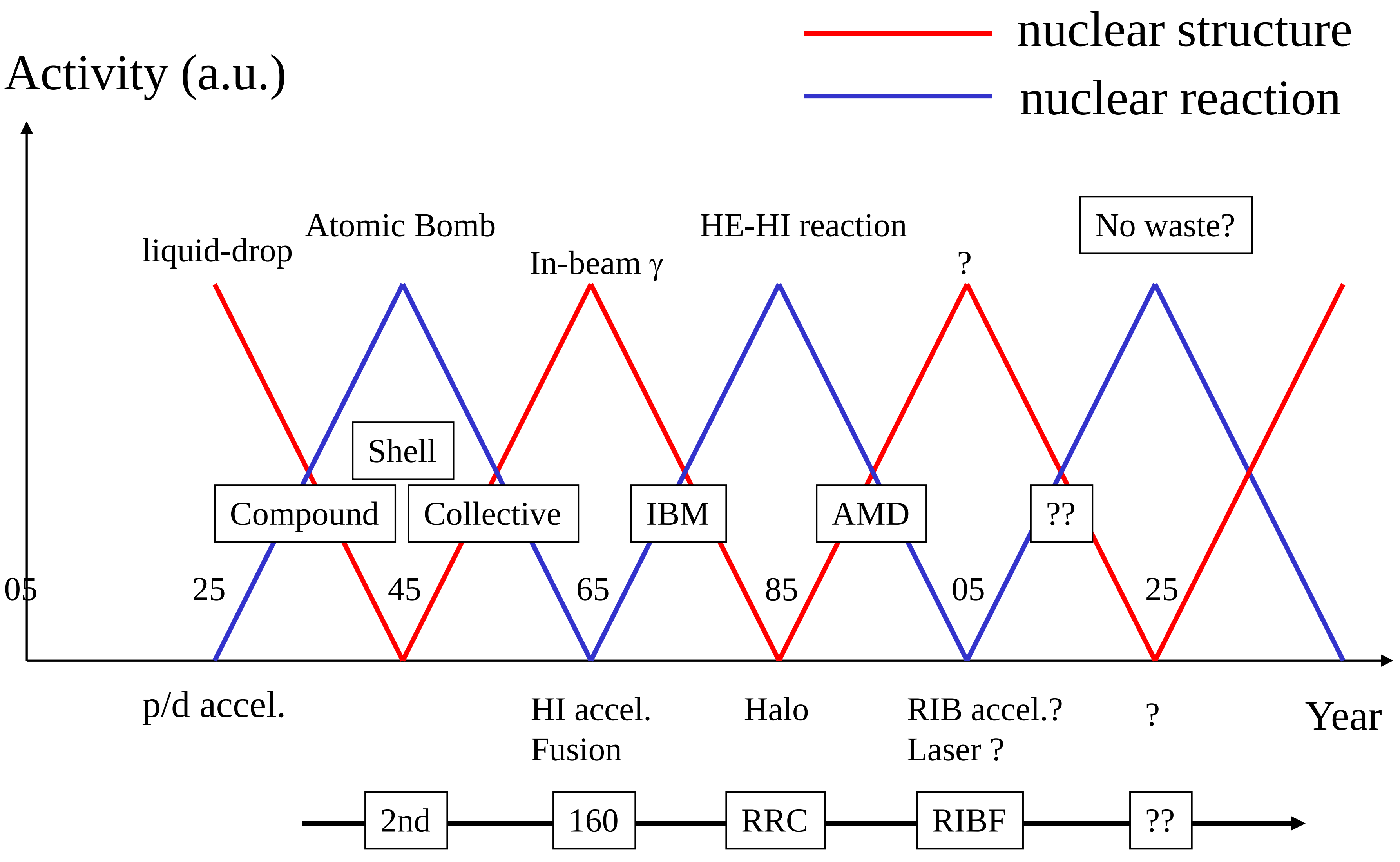


➢ Physics of superheavy elements

- ✓ theory of multi-nucleon transfer reactions
- ✓ combining the coupled-channels approach with Langevin calculation
- ✓ estimate of fusion cross sections with neutron-rich beams
- ✓ theory of nuclear fission
- ✓ "beyond mean field" approach for nuclear reactions (description of many-particle tunneling)

strong experiment-theory couplings: essential

Sakurai-san's slide (2008)



Sakurai-san's slide (2008)